

THE DESIGN AND TEST OF A
HIGH SPEED ENGINE INDICATOR

by

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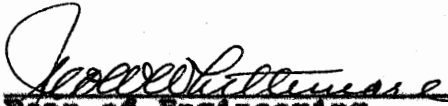
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TABLE OF CONTENTS

Chapter		Page
I.	INTRODUCTION.....	2
II.	REVIEW OF LITERATURE.....	4
III.	THE INVESTIGATION.....	9
	A. The Object.....	9
	B. The Apparatus.....	9
	1. A Balanced Pressure Diaphragm Indicator.....	9
	2. Design Features of the Cylinder Pressure Indicator.....	17
	C. The Accessory Apparatus.....	21
	D. The Method of Procedure.....	26
	E. The Method of Calculation.....	28
	F. The Results.....	33
IV.	DISCUSSION OF THE RESULTS.....	35
V.	CONCLUSIONS.....	38
VI.	FINAL SUMMARY.....	39
VII.	RECOMMENDATIONS.....	40
VIII.	ACKNOWLEDGEMENT.....	41
IX.	BIBLIOGRAPHY.....	42
	A. Cited Literature.....	42
	B. General Literature.....	43
	APPENDIX.....	44
	A. Tables and Diagrams.....	45
	B. Indicator Drawings.....	53
	VITA.....	63

I

INTRODUCTION

In order to study the performance of an internal combustion engine more effectively than is ordinarily possible with an electric dynamometer, it is necessary to have a pressure-volume diagram (commonly referred to as an indicator diagram) of the engine cycle. With an indicator diagram, cylinder pressure and volume at any point in the cycle may be read directly. Other parameters such as the indicated mean effective pressure and the indicated horsepower may be calculated from such a diagram. The indicator diagram may be used to show the effect of changes in engine operating conditions; for example, any change in ignition or valve timing, air-fuel ratio, load and speed as well as the progressive wear of the piston rings or valves, will change the pressure record of the indicator diagram. (1)* In addition, the indicator diagram provides a means of studying the actual compression and expansion paths of the cycle, ignition delay, and the time required for the complete combustion of the fuel-air mixture within the cylinder.

* Numbers in parenthesis refer to corresponding literature found in Literature Cited, Section IX.

Before an indicator diagram can be used for such studies, it must be determined whether or not the engine indicator used in obtaining the indicator diagram is sufficiently accurate for this purpose. In this study, the accuracy of the engine indicator will be ascertained by comparing the indicated horsepower of an engine as obtained by means of a Sprague-type cradle electric dynamometer and as calculated from an indicator diagram. The indicated horsepower, which is taken as the sum of the brake horsepower and the horsepower required to motor the engine, is defined as the power developed within the cylinder of the engine. (2) Therefore, if the brake horsepower and the horsepower required to motor the engine are determined by means of the electric dynamometer and summed up to give the indicated horsepower, the result should be approximately equal to the indicated horsepower as calculated from an indicator diagram. If the results thus obtained are approximately equal, the indicator designed for this study may be considered sufficiently accurate for use in the study of the internal combustion engine cycle.

II

REVIEW OF LITERATURE

To obtain an indicator diagram of an engine cycle, it is necessary to have an engine indicator that will operate satisfactorily throughout the entire speed range of the engine.

In a report to the National Advisory Committee for Aeronautics, ⁽³⁾ H. C. Dickenson and F. B. Newell give a brief history of the development of engine indicators. Prior to 1917, there were several types of mechanical engine indicators in use on internal combustion engines, some of them of the type that are still used on steam engines and air compressors. There were also mechanical indicators designed specifically for use on internal combustion engines. The latter were designed from the standpoint of reducing the inertia in the moving parts of the indicator. Both of these early types of indicators were, and still are, entirely satisfactory for use on large, slow speed internal combustion engines.

However, these mechanical indicators, although designed for low inertia are of little value at engine speeds in excess of 1000 revolutions per minute. At the higher speeds, friction, inertia, and backlash in the moving parts of the indicator combine to produce

serious errors in the indicator diagram. In addition to this, heavy springs, when used in engine indicators in order to record the high pressure portion of a cycle, completely nullify any events that may occur during the low pressure portion of the cycle. Mechanical indicators, when attached to an engine, increase the clearance volume of the cylinder, thus decreasing the compression ratio. (4) The detrimental effect of this decrease in compression ratio is more pronounced where the displacement volume of the cylinder is small.

These disadvantages have led to the development of several types of non-mechanical pressure indicators. As these non-mechanical indicators record pressures only, auxiliary devices must be used in conjunction with the pressure indicator in order to produce a volume scale. The auxiliary devices usually indicate either time or the angular displacement of the engine crankshaft both of which may be correlated with cylinder volume to produce the conventional pressure volume diagram.

The non-mechanical engine pressure indicators can be divided into two general groups, (5) namely; the instantaneous indicating type, and the point-to-point indicating type. The piezoelectric, magnetic, strain gage, and variable capacitance types of pressure indicators fall under the first group in that they show the

entire pressure record of each engine cycle on an oscilloscope. On the other hand, the balanced-pressure diaphragm type of indicator, which is to be used in this study, falls under the point-to-point indicating group. This type of indicator records the pressure at only one point in the engine cycle at a time and the pressure record obtained is the average of a great many engine cycles.

Dickenson and Newell give the principle of operation of a balanced-pressure diaphragm indicator as follows:

"The principle involved is the balancing of the engine cylinder pressure against a measured pressure on opposite sides of a metal diaphragm of negligible stiffness." (6)

In 1920, the National Advisory Committee for Aeronautics found that the balanced-pressure diaphragm type of indicator "proved satisfactory for use under conditions of actual practice from 200 to 2,600 revolutions per minute (the highest speed available for test), and from ten pounds per square inch below atmospheric pressure to 1,000 pounds per square inch above." (7) The indicators were convenient to use and were as accurate as the gages used in recording the pressures.

G. I. Laserson, in his thesis which was submitted at Columbia University, used a balanced-pressure diaphragm type of indicator to study the chemiluminescent

radiation in internal combustion engines because of "its inherent accuracy and simplicity."⁽⁸⁾ This type of indicator does not depend upon the elastic deformation of some member of the indicator for its pressure indication (as in the strain gage type) and the temperature dependence of the modulus of elasticity has no influence on the indicator operation. Another advantage of the balanced-pressure diaphragm type of indicator is that the auxiliary equipment which is required is extremely simple and inexpensive.

There are three possible sources of error in this type of indicator. These sources of error are listed by Laserson⁽⁹⁾ as: "1, The difference between cylinder pressure and diaphragm balancing pressure at the time the diaphragm makes or breaks contact; 2, the difference between the balancing pressure and the pressure indicated by the pressure gages; and 3, the time lag of the instrument."

The pressure differential required to deflect the diaphragm can be found and applied as a correction factor to reduce the effect of the first source of error as mentioned above. The second source of error can be minimized by careful calibration of the gages. Taylor and Draper⁽¹⁰⁾ found the time lag of the instrument to be in the order of three or four microseconds.

In the N. A. C. A. Report Number 359 by Spanagle and Collins, ⁽¹¹⁾ the most serious argument against the balanced pressure diaphragm type of indicator was the possibility of diaphragm failure because of overheating when located near the combustion chamber wall. However, previous experience had showed that a "small diameter diaphragm remained sufficiently cool to prevent rupture and it was thought that any heat effect should increase the sensitivity of the diaphragm."

W. J. R. Roach and C. G. Hempson state ⁽¹²⁾ that the "pressure diagram obtained (with a balanced-pressure diaphragm indicator) is of large size, (and) the time base is accurate and linear." In addition, "the pressure recording mechanism can be calibrated with a high degree of accuracy."

This type of indicator is a popular instrument for obtaining indicator cards on reciprocating engines, air compressors, pumps, and the like, ⁽¹³⁾ and it has been used extensively by Companies such as General Motors and the Ethyl Corporation for studies of engine and fuel performance. ⁽¹⁴⁾

III

THE INVESTIGATIONA. The Object

The object of this investigation is the design and the test of a balanced-pressure diaphragm engine indicator for use on internal combustion engines, furthermore, the primary objective in this design is to produce a workable engine cylinder pressure indicator for the least possible cost.

B. The Apparatus and Its Operation

1. A balanced-pressure diaphragm indicator.

The balanced-pressure diaphragm engine indicator consists of a balanced-pressure diaphragm type of cylinder pressure indicator, an electronic pressure balance indicator, and a timing disc.

- a. The balanced-pressure diaphragm cylinder pressure indicator was designed by the author, utilizing, where possible, the best features of several pressure indicators of this type. The operation of the balanced-pressure diaphragm engine cylinder pressure indicators is as follows: A measured pressure

(hereafter to be termed "the reference pressure") is applied to the upper side of a thin metal diaphragm which is clamped between two perforated metal discs. The lower side of the diaphragm is exposed to the engine cylinder pressure. The reference pressure forces the diaphragm away from the upper perforated disc and the electrode contact which passes through the upper disc, thereby breaking the electric circuit between the disc and the electrode. Whenever the pressure in the engine cylinder reaches a point that approaches the reference pressure, the diaphragm moves into contact with the upper perforated disc and the electrode tip. When the diaphragm makes contact with the electrode, it closes the control circuit of the electronic pressure balance indicator. This circuit will be discussed in Section 1-b.

When the engine cylinder pressure is greater than the reference pressure, the diaphragm will remain in contact with the electrode tip. As the cylinder pressure falls below the reference pressure, the

diaphragm will move away from the electrode and break the control circuit of the electronic pressure balance indicator.

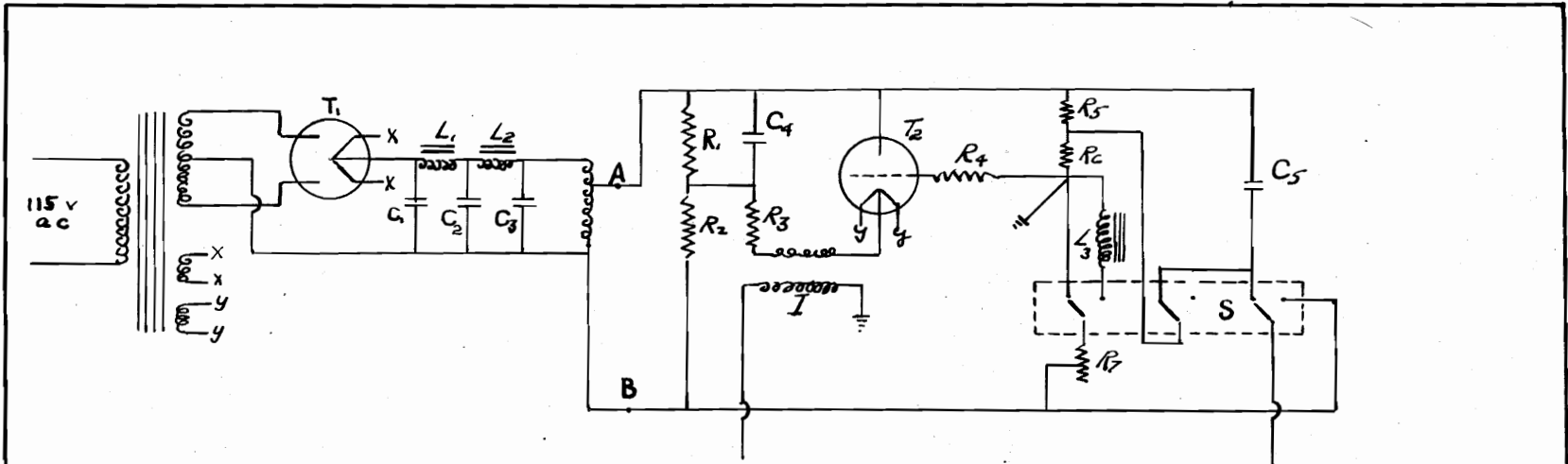
- b. The electronic pressure balance indicator circuit was first developed by E. S. Taylor and C. S. Draper⁽¹⁵⁾ with the aid of the Electrical Engineering Department of the Massachusetts Institute of Technology. The circuit used by the author was modified for his study in order to make use of existing equipment in the Mechanical Engineering Laboratory at the Virginia Polytechnic Institute. However, the operation of the pressure balance indicator remains unchanged from that developed by Taylor and Draper.

The function of the electronic pressure balance indicator is to supply a signal at the moment the diaphragm opens or closes the pressure balance indicator control circuit. This signal, when applied to the timing disc, shows the point in the engine cycle at which the engine cylinder pressure balances the known reference pressure.

The electronic pressure balance indicator consists of the power supply and the pressure balance indicator circuit. The

power supply is shown at the left of the points A and B in Figure 1 and consists of a full wave rectifier with three filter stages, producing an output of 350 volts DC with negligible ripple. The electronic pressure balance indicator circuit is shown at the right of the points A and B in Figure 1 and its purpose is to distinguish between the opening and closing of the indicator diaphragm contacts and to provide a spark discharge on the timing disc at the instant of contact operation.

The most important element in the pressure balance indicator circuit is the thyatron tube (RCA 884). This is a three element tube that has two characteristics. First, by maintaining a negative grid bias, the grid controls the starting of the current flow through the tube but has no control over the current flow once it has been established. The only way the grid can regain control of the current flow is to have the current flow brought to zero. The second feature is that the tube can handle large currents (up to 75 ma) with a very small voltage drop across the tube.



TO TIMING DISC

TO DIAPHRAGM CONTACTS

- | | | |
|--|---|------------------------------|
| $R_1 \text{ \& } R_5 = 100\,000\ \Omega$ | $C_1 \text{ \& } C_2 = 2.5\ \text{mf}$ | $L_3 = 0.28\ \text{hys.}$ |
| $R_2 = 17\,500\ \Omega$ | $C_3 = 5\ \text{mf}$ | $S = \text{T.P.D.T. SWITCH}$ |
| $R_3 = 20\ \Omega$ | $C_4 = 0.25\ \text{mf}$ | $T_1 = \text{RCA } 5Y3$ |
| $R_4 = 10\,000\ \Omega$ | $C_5 = 0.005\ \text{mf}$ | $T_2 = \text{RCA } 884$ |
| $R_6 \text{ \& } R_7 = 5\,000\ \Omega$ | $L_1 \text{ \& } L_2 = 20\ \text{hys.}$ | $I = \text{INDUCTION COIL}$ |

PRESSURE BALANCE INDICATOR
CIRCUIT DIAGRAM

FIGURE 1

Figure 1 shows the pressure balance indicator circuit diagram as connected for operation at the instant the diaphragm contacts close.

While the diaphragm contacts are open, and the thyatron tube is non-conducting (no current flow), the capacitor, C_4 , charges to nearly 350 volts. This electric potential is impressed around the circuit which is composed of the thyatron, T_2 , the capacitor, C_4 , the primary winding of the induction coil, I , and the resistance, R_3 . At the same time there is a current flowing from positive to negative through the resistances R_1 , and R_2 . Hence, there is a voltage drop across the resistance R_2 which raises the potential of the thyatron filament about 25 volts with respect to the negative lead permitting negative biasing of the grid as described below.

In the diaphragm circuit, there is a current flowing through the resistances R_5 , R_6 and the variable resistance R_7 . The variable resistance is adjusted to such a value that will keep the grid sufficiently

negative to maintain the grid in a non-conducting state. When the diaphragm contacts close, R_6 is short-circuited. This short circuit raises the potential of the grid an amount corresponding to the voltage drop that formerly existed across R_6 , permitting the thyratron tube to start conducting. The capacitor, C_4 , then discharges through the primary winding of the induction coil, inducing a high potential in the secondary winding of the coil which in turn provides the necessary spark discharge on the timing disc. The discharge of the capacitor, C_4 , is oscillatory due to the inductance of the induction coil, and hence, the current in the thyratron actually reaches zero, allowing the grid to regain control of the current flow.

When the triple-pole, double-throw switch is in the position opposite from that shown in Figure 1, the pressure balance indicator will operate at the instant the diaphragm contacts open. While the diaphragm contacts are closed, the choke coil, L_3 , and the resistance R_7 , are short-circuited,

thereby causing an increase of the negative bias on the grid. When the diaphragm contacts open, a voltage is applied across the choke coil, L_3 , and the resistance, R_7 , which raises the grid bias to a positive potential with respect to the cathode and the thyratron tube then starts conducting. The capacitor, C_4 , then discharges through the primary winding of the induction coil. The high potential of the secondary winding of the induction coil provides the spark necessary to indicate the pressure balance.

c. The function of the timing disc is to show the angular position of the engine crankshaft at the moment the engine cylinder pressure balances the reference pressure within the cylinder pressure indicator.

The timing disc is mounted on the dynamometer shaft extension and revolves at engine speed. An annular ring, graduated in degrees, is mounted on the dynamometer by means of insulating wooden blocks. The annular ring is positioned so that its inner edge is in the same plane as the timing disc. A pointer on the timing disc is adjusted so

that it is approximately 0.05 inch from the inner edge of the annular ring.

The operation of the timing disc is as follows: The high potential output of the secondary winding of the induction coil in the pressure balance indicator is applied to the annular ring at the moment a pressure balance occurs within the cylinder pressure indicator. Since the annular ring is insulated from the dynamometer frame, the high potential causes a spark to jump from the graduated ring to the pointer on the timing disc, which is grounded to the dynamometer frame. The crank angle at which a pressure balance occurs within the cylinder pressure indicator can be observed when the spark jumps from the graduated ring to the timing disc.

2. Design features of the cylinder pressure indicator.

The balanced-pressure diaphragm engine cylinder pressure indicator was made in the Machine Shop of the Industrial Engineering Department of the Virginia Polytechnic Institute.

The indicator consists of thirteen parts, twelve of which are shown in Figure 2(a).^{*} The parts are as follows: 1 and 3, the lower and upper diaphragm supports; 2, the diaphragm; 4, the diaphragm pressure ring; 5, the diaphragm holder; 6, the reference pressure chamber; 7, the compression nut; 8, the lower Teflon insulator; 9, the electrode guide; 10, the electrode; 11, the electrode adjuster frame; and 12, the electrode adjuster nut. The remaining part, which is the upper Teflon insulator, is not shown in the figure. Of the twelve parts listed above, parts 5, 6, and 7 were machined with standard threads and screwed together to hold the remaining parts in their proper positions.

The most important single element of the cylinder pressure indicator is the diaphragm. The diaphragm must be flexible enough to be deflected away from the electrode by a small pressure differential across the diaphragm, yet it must be strong enough to withstand the highest pressure differential that it may encounter.

^{*} Detail drawings of each part of the cylinder pressure indicator and an assembly drawing are included in the pocket inside the back cover of the thesis.

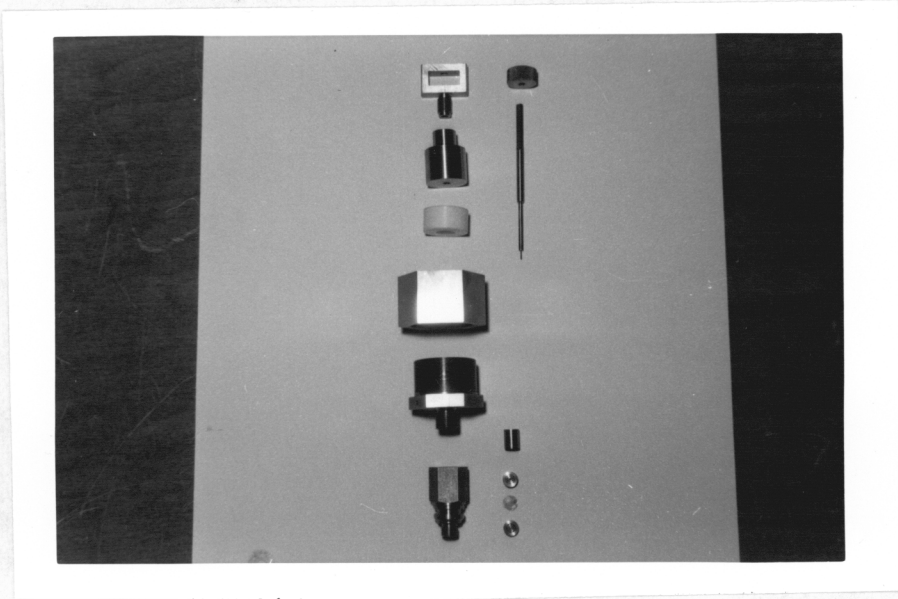


Figure 2(a)

The Dis-assembled Cylinder Pressure Indicator

The disassembled cylinder pressure indicator.

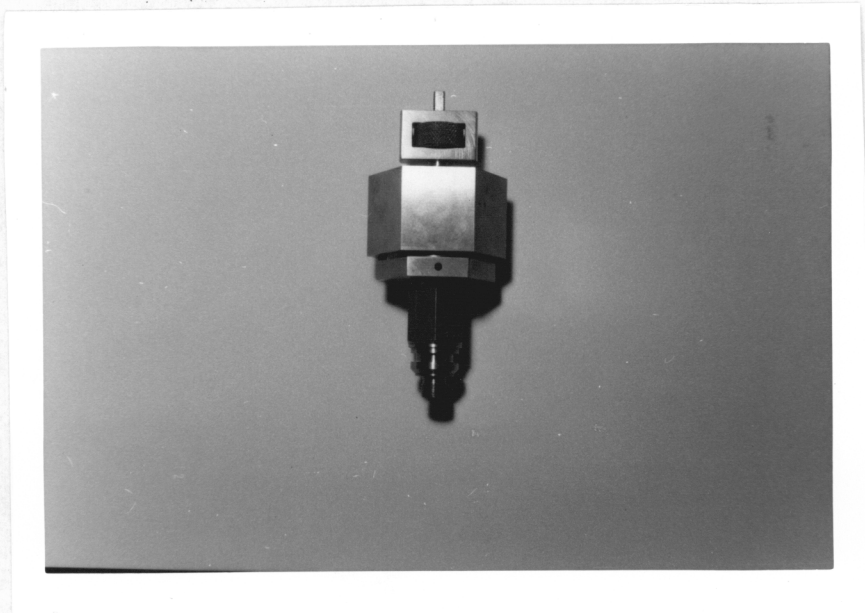


Figure 2(b)

The Assembled Cylinder Pressure Indicator

In addition to this, the diaphragm must resist burning, dimpling, and the corrosive effect of combustion gases within the cylinder. the diaphragm used in this indicator was made of stainless steel feeler gage stock, 0.003 inch thick and 1/2 inch in diameter.

The diaphragm holder, which receives the diaphragm and the upper and lower diaphragm supports, is threaded on its small end to fit into a standard 14 mm spark plug hole. The opposite end of the diaphragm holder is threaded to receive the reference pressure chamber.

The diaphragm pressure ring is inserted in the diaphragm holder between the upper diaphragm support and the reference pressure chamber. By screwing the reference pressure chamber into the diaphragm holder, a force is applied to the upper diaphragm support, by way of the pressure ring, thereby clamping the diaphragm in position. The assembly of these parts permit the reference pressure medium to act on the upper side of the diaphragm.

The electrode guide has for its purpose the proper alignment of the electrode with respect to the upper diaphragm support. The electrode

guide fits into the lower Teflon insulator, which, in turn, is placed into the large end of the reference pressure chamber. The small end of the electrode guide is drilled and tapped to receive the electrode adjuster frame.

The hexagonal compression nut is threaded internally to receive the large end of the reference pressure chamber and is screwed down over the electrode guide, thereby compressing the upper and lower Teflon insulators, which seals the reference chamber against any pressure loss around the electrode guide.

The electrode adjuster, which consists of the electrode adjuster frame and the electrode adjuster nut, served as a means of adjusting the electrode to compensate for any expansion and contraction of the indicator because of changes in the operating temperature.

C. The Accessory Apparatus

1. Christie Variable Compression Ratio Engine
Bore 3.0625", Stroke 4.5"
Horsepower 4.9 @ 1700 rpm
Compression ratio - Variable from 3.1 to 8.1
Christie Machine Works
222 Howard Street
San Francisco, California

- 2. Electric Dynamometer**
 4 Horsepower, 230 volts, 15.5 amps
 Type K-3, Shunt Wound, Es.No. K3-73
 Serial No. 804597, Continuous Duty 40°C rise
 2000-4000 rpm, S.S. K3-77
 Diehl Manufacturing Company
 Elizabethport, N. J.

3. Dynamometer Control Panel*

This panel includes:

- a. Direct Current Ammeter
 40-0-40 amps, Type DD6, Model 8DD6A-V17
 Serial No. 1028499, General Electric USA
- b. Direct Current Voltmeter
 0-300 volts, Type DD6 Model 8DD6 VAS6
 Serial No. 1025824, General Electric USA
- 4. Motor Generator Set for Supplying Direct Current to the Dynamometer**
- a. General Electric Induction Motor
 Model 69A186, Type FT048-4-10-1800
 Form CL, 3 phase, 60 cycles, 250v
 Speed Full Load - 1740 rpm, No. EJ1162
 10 Hp. Continuous operation 50°C rise
 General Electric Corporation
 Schenectady, N. Y.
- b. Direct Current Generator
 Model 47A57, Type CD65
 Form AL, Compound Wound
 24 amp, 250/250 volt, Speed 1800 rpm
 No. 1663447, 6 KW
 Continuous Operation 50°C rise
 General Electric Corporation
 Schenectady, N. Y.
- c. Starting Mechanism
- 1) Push Button Station
 CR 2940-8579J
 Maximum Volts 600
 General Electric Corporation

* For the dynamometer circuit diagram, see Figure 4, page 24.

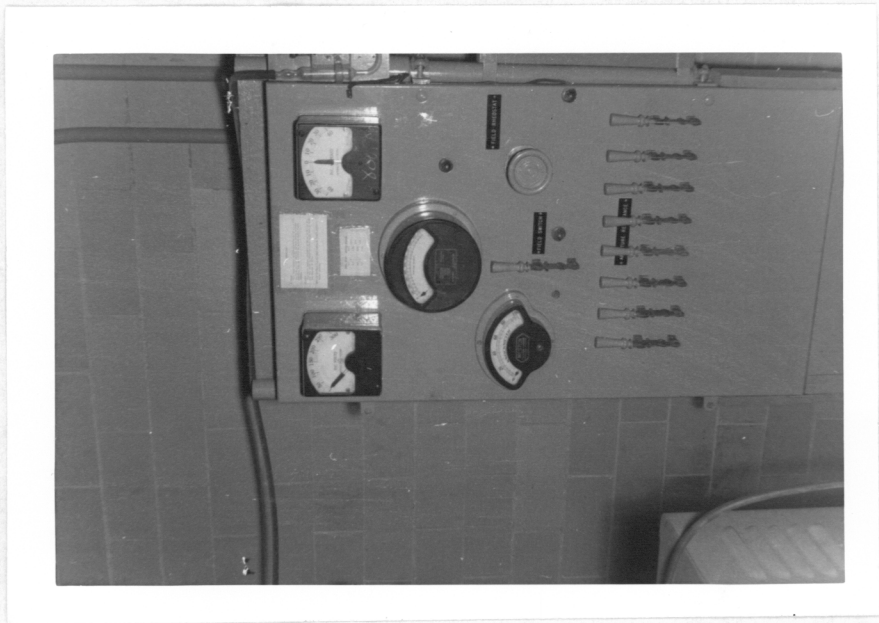


Figure 3(b)
The Dynamometer Control
Panel

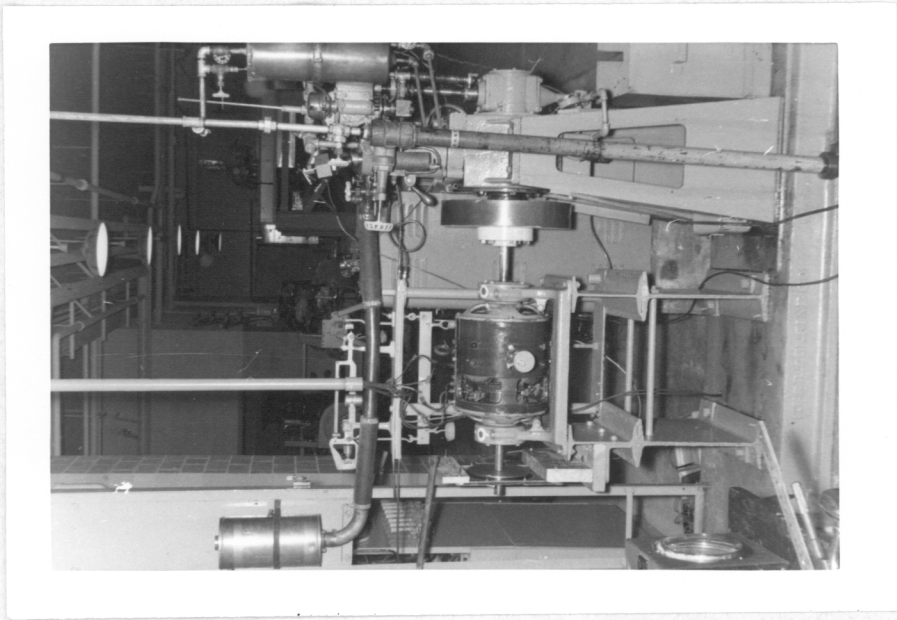
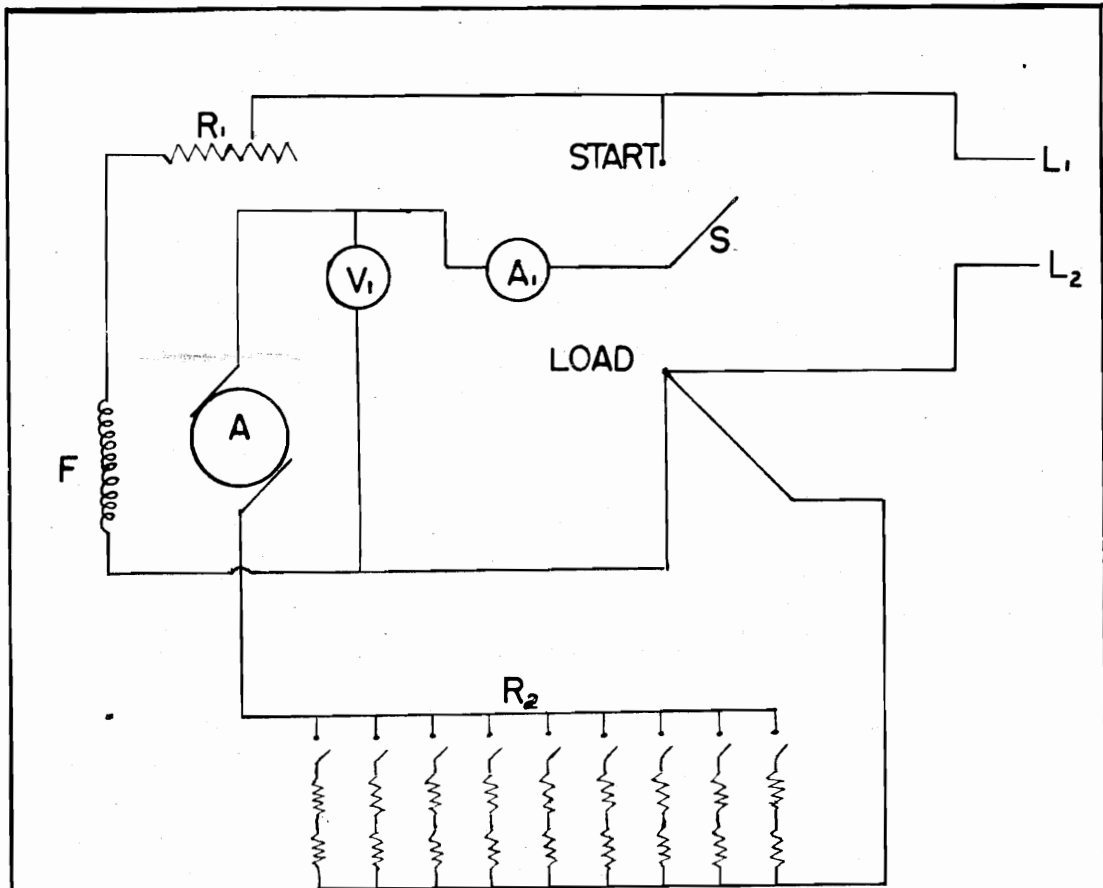


Figure 3(a)
The Christie Test
Engine and Dynamometer



DYNAMOMETER CIRCUIT DIAGRAM

L_1 & L_2 - LEADS FROM MOTOR-GENERATOR

R_1 - VARIABLE FIELD RESISTANCE

F - DYNAMOMETER FIELD

R_2 - ARMATURE RESISTANCES

A - DYNAMOMETER ARMATURE

S - SINGLE-POLE, DOUBLE-THROW SWITCH
(NOT SHOWN IN FIGURE 3(b))

V_1 - DC VOLTMETER

A_1 - DC AMMETER

FIGURE 4

- 2) Magnetic Switch
CR7006-D4, Cat. 1773589G2
200 Volts at 60 Cycles
General Electric Corporation
5. Industrial Analyser, used in adjusting the indicator electrode:

Model 630, Superior Instrument Company
New York, New York, USA
6. Strobotac used to determine engine speed:

Type 631 B, Serial No. 6107,
Range 600-14500 rpm
General Radio Company
Cambridge, Massachusetts
7. Nitrogen Gas, used as reference pressure:

220 cu.ft. @ 2200 psi purchased from
Southern Oxygen Company
Roanoke, Virginia
8. Pressure Regulating Valve used to control the reference pressure:

Style No. 511, Serial No. 36863
0-3000 psi cylinder pressure
0-2000 psi working pressure
Hoke Phoenix Regulator
9. Reference Pressure Gage, to measure positive reference pressures:

0-1000 psi
No. 12254
U. S. Guage Company
10. Reference Pressure Gage, to measure reference vacuum pressures:

0-30 in Hg Vacuum, 0-15 psi pressure
No. BN-1
Lonergan, Philadelphia
11. An Automotive Type Engine, used as a source of vacuum.

D. The Method Of Procedure

The following procedure was used in testing the balanced-pressure diaphragm engine indicator.

The cylinder pressure indicator was mounted on the cylinder head of the Christie Variable Compression Ratio engine through an opening that was provided for a Midgely bouncing pin knockmeter.

Before starting the engine, a check was made of the fuel and oil supply, the cooling water was turned on, and the engine flywheel was rotated in its reverse direction in order to assure that the dynamometer would turn the engine at least one full revolution before reaching its initial compression stroke. This reduced the stalling effect resulting from the compression produced during the initial compression stroke when starting the engine.

The engine was started by supplying the dynamometer with 220 volts from a direct current source. As soon as the engine fired, the dynamometer starting circuit was opened. The engine was then allowed to run at no load until the recommended cooling water temperature was established, whereupon the throttle was opened slightly and a small load applied by means of the electric dynamometer. The engine was allowed to run under these conditions until the cylinder pressure indicator had

become thoroughly warmed. The throttle was then opened fully and the engine loaded by means of the dynamometer until the desired engine speed was obtained. The indicator electrode was adjusted until the Superior industrial analyser indicated the diaphragm contacts were regularly opening and closing. The electronic pressure balance indicator was then connected to the cylinder pressure indicator and the actual test of the engine indicator was begun.

With the pressure balance indicator selector switch in the "Make" position, (i. e. So that the indicator functions when the diaphragm and electrode make contact) the reference pressure was increased in increments of 10 psig from atmospheric pressure to the point at which the reference pressure was greater than the maximum cylinder pressure and the pressure balance indicator ceased to indicate.

The selector switch was then moved to the "Break" position, (i. e. So that the pressure balance indicator functions when the electrode breaks contact with the diaphragm and the pressure reduced in increments of 10 psig to atmospheric pressure. The reference pressure was then further reduced in increments of two inches Hg gage until the pressure balance indicator again ceased to indicate. The selector switch was then returned to

its "Make" position and the reference pressure raised to atmospheric pressure in increments of two inches Hg gage.

At each pressure setting throughout the entire pressure range, a reading of the engine crank angle was simultaneously taken from the timing disc at the point where the pressure balance occurred.

As a part of the test of the indicator, readings were taken of the brake load and the engine speed for the purpose of calculating the brake horsepower.

Data for determining the friction horsepower or, the power required to motor the engine, was found by motoring the engine by means of the dynamometer and recording the dynamometer load and speed.

E. The Method of Calculation

The data used in the following sample calculations was taken from Test II of the indicator:

1. Brake Torque, $T = FL$

where T = brake torque, lb-ft
 F = brake load, lbs
 L = length of brake arm, ft

$$T = 18 \times \frac{8.4}{12}$$

$$T = 12.6$$

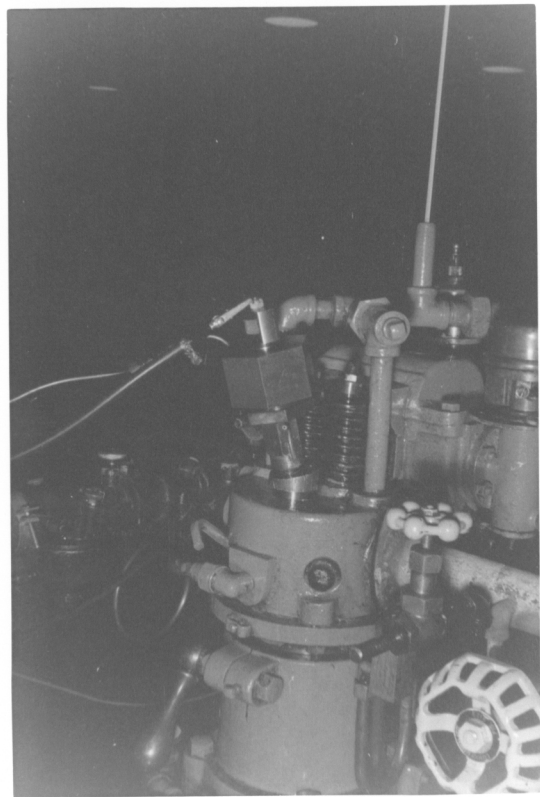


Figure 5(a)
The Indicator As Mounted
on the Christie Engine

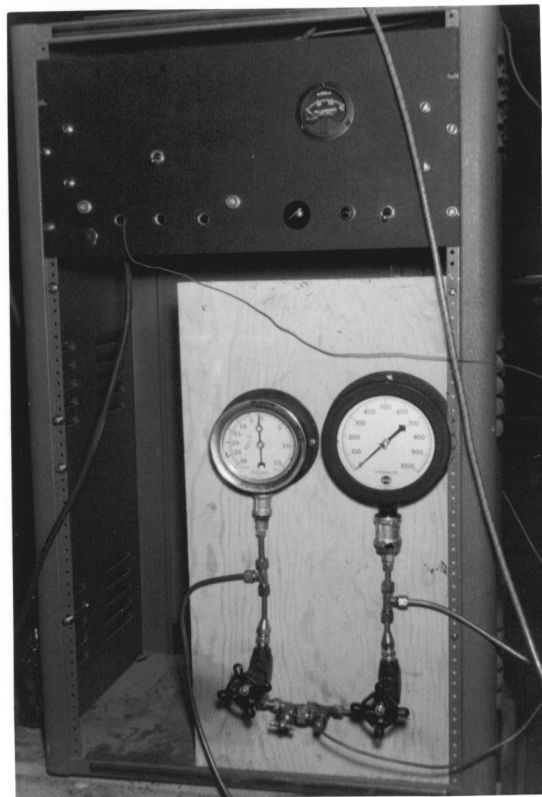


Figure 5(b)
The Electronic Pressure
Balance Indicator and
Reference Pressure Gages

$$2. \text{ Brake Horsepower, } BH_p = \frac{FN}{7500}$$

where BH_p = brake horsepower
 F = brake load, lbs
 N = engine speed, rpm
 7500 = dynamometer constant

$$BH_p = \frac{18 \times 1345}{7500}$$

$$BH_p = 3.22$$

3. Brake Mean Effective Pressure,

$$P_{bme} = \frac{33000 \times BH_p}{LAN'}$$

where P_{bme} = brake mean effective pressure, psi
 BH_p = brake horsepower, item 2
 L = length of stroke, ft
 A = Area of piston, sq.in.
 N' = Number of power strokes per minute

$$P_{bme} = \frac{33000 \times 3.22}{\frac{4.5}{12} \times 7.38 \times \frac{1345}{2}}$$

$$P_{bme} = 57.2 \text{ psi}$$

$$4. \text{ Friction Horsepower, } FH_p = \frac{F' N''}{7500}$$

where FH_p = friction horsepower
 F' = dynamometer load lbs
 N'' = dynamometer speed, rpm
 7500 = dynamometer constant

$$FH_p = \frac{9 \times 550}{7500}$$

$$FH_p = 0.66$$

5. Cylinder Clearance Volume,

$$V_c = \frac{V_d}{r_c - 1} + V_a$$

where V_c = cylinder clearance volume, cu in
 V_d = piston displacement volume, cu in
 r_c = compression ratio
 V_a = clearance volume increase due to the indicator adapter, cu in

$$V_c = \frac{33.2}{7-1} + 0.317$$

$$V_c = 5.557$$

6. Actual Compression Ratio, $r_c = \frac{V_c + V_d}{V_c}$

where r_c = compression ratio
 V_c = cylinder clearance volume, cu in
 V_d = piston displacement volume, cu in

$$r_c = \frac{5.557 + 33.2}{5.557}$$

$$r_c = 6.96$$

7. Conversion of Crank Angle to Cylinder Volume,

$$V'_c = \left[R(1 - \cos \theta) + \frac{R \sin^2 \theta}{2L} \right] A + V_c$$

where V'_c = cylinder volume, cu in
 R = length of crank throw, in
 θ = crank angle, deg
 L = length of connecting rod, in
 A = area of piston, sq in
 V_c = cylinder clearance volume, cu in (item 5)

$$V'_c = \left[2.25(1 - \cos 90) + \frac{2.25 \sin^2 90}{2 \times 9.5} \right]$$

$$\times 7.38 + 5.557$$

$$V'_c = 24.34 \text{ cu in}$$

8. Determination of the Constant, n , for the Polytropic Compression and Expansion Paths,

$$n = \frac{\log P_2 - \log P_1}{\log V_1 - \log V_2}$$

where P_1 - pressure at the beginning of the compression or expansion path, psi
 P_2 - pressure at the end of the compression or expansion path, psi
 V_1 - volume at the beginning of the compression or expansion path, cu in
 V_2 - volume at the end of the compression or expansion path

$$n = \frac{\log 150 - \log 50}{\log 16 - \log 7}$$

$$n = 1.332$$

F. The Results

The results of this investigation are in the form of tables and curves which are given in Section X.

1. The Tables.

Included in each of the Tables I, II, and III, are the observed values of throttle setting, spark advance, brake load, engine speed, and barometric pressure. The observed crank angle at which a pressure balance occurred within the cylinder pressure indicator for each setting of the reference pressure are included in tabular form in each of the three tables.

The calculated values of brake torque, brake horsepower, brake mean effective pressure, compression ratio, and friction horsepower for each test are also included in the same tables.

2. The Curves.

Curve I is a plot of engine crank angles versus cylinder volumes. The purpose of this curve is to provide a means of converting to cylinder volume from crank angle degrees when plotting the pressure volume relations.

Curves II, III, and IV show the results calculated from the data obtained from the three tests of the balanced-pressure diaphragm engine indicator. These curves show the pressure-volume relationship for both the compression and expansion paths of the engine cycle during Tests I, II, and III of the engine indicator. The values used in plotting the pressure-volume paths were determined from data given in Tables I, II and III.

IV

DISCUSSION OF RESULTS

An examination of several textbooks and handbooks* show that the average indicator diagram from spark ignition engines approximate a polytropic process $PV^n = C$, for the compression and expansion paths. The exponent, n , for both the compression and expansion paths varies from 1.25 to 1.35, 1.3 being the generally accepted value for n .

The results calculated from the data obtained in Test I, II, and III show that the exponent, n , varied from 1.14 to 1.33 for the compression paths and from 1.29 to 1.32 for the expansion paths.

* J. Kenneth Salisbury, editor, Power Volume, Kents Mechanical Engineers Handbook, Twelfth Edition, (New York: John Wiley and Sons, Inc., 1950), p. 13-08.

Joseph A. Polson, Internal Combustion Engines (New York: John Wiley and Sons, Inc., 1942), p. 122.

Joseph Liston, Aircraft Engine Design (New York: McGraw-Hill Book Company, 1942), p. 29.

Lester C. Lichty, Internal Combustion Engines (New York: McGraw-Hill Book Company, 1939), p. 59.

Lionel S. Marks, editor, Mechanical Engineers Handbook (New York: McGraw-Hill Book Company, 1951), p. 298.

These results indicate that the engine indicator is reasonably accurate for that portion of the indicator diagram in the region on the compression and expansion paths where the rate of pressure change is large.

The engine indicator did not function properly during the combustion process and the intake and exhaust portions of the cycle, hence a complete indicator diagram of the engine cycle could not be obtained. Therefore, the values of the exponent, n , in the equation $PV^n = C$, for polytropic compression and expansion as calculated from the test data, were compared with the values of n found in the reference material indicated above. This method of determining the accuracy of the engine indicator was used in lieu of the comparison of the indicated horsepowers as originally planned.

It is believed that the cylinder pressure indicator failed to operate properly during the low pressure portion of the engine cycle because the 0.003 inch thick diaphragm was too rigid to be deflected by the small unbalanced pressures across the diaphragm. The indicator failed to operate properly during the combustion process because of electrical interference from the engine ignition system. The effect of this electrical interference is explained as follows:

The high frequency leakage from the engine ignition system caused the thyatron tube to lose

control of the current flow, thereby resulting in a discharge of the capacitor, C_4 , (See Figure 1, p. 13). The discharge of the capacitor caused a spark to jump from the graduated ring to the timing disc at 15 deg before top dead center, the same point in the engine cycle at which the engine ignition spark occurred. After the capacitor, C_4 , was discharged by the ignition system leakage, there could be no indication of a pressure balance within the cylinder pressure indicator until the capacitor had sufficient time to regain its charge. For this reason, crank angle values could not be obtained for plotting the pressure-volume relations of the engine cycle from 15 deg before top dead center on the compression path to a point approximately 90 deg after top dead center on the expansion path.

V

CONCLUSIONS

The following conclusions were derived from the test of the balanced-pressure diaphragm engine indicator:

A. The indicator provided accurate data for that portion of the engine cycle where the operation of the indicator was not affected by extraneous electrical interference.

B. Because of electrical interference from the engine ignition system, the indicator did not provide sufficient data to construct a complete cycle diagram.

C. From the tests it is apparent that with the isolation of the apparatus from electrical interference, the indicator could be used to determine the pressure-volume relations of a complete engine cycle.

VI

SUMMARY

The purpose of the study was to design an engine indicator for use on high speed internal combustion engines.

The balanced-pressure diaphragm engine indicator was designed by the author. It was built in the shops of the Industrial Engineering Department and tested on a single-cylinder, four stroke cycle, spark ignition engine in the Mechanical Engineering Laboratory of the Virginia Polytechnic Institute.

The results of the test show that the indicator was accurate over certain portions of the engine cycle, namely; the compression and expansion strokes.

The indicator did not function properly throughout the complete engine cycle because electrical interference from the ignition system caused the thyatron tube to lose control of the electronic indicating circuit.

It is believed that the indicator would have functioned properly for the entire cycle had the indicator and its associated electrical apparatus been shielded from the engine ignition system.

VII

RECOMMENDATIONS

The following recommendations suggest steps toward making the balanced-pressure diaphragm engine indicator operate satisfactorily:

1. The leads from the engine mounted cylinder pressure indicator to the electronic pressure balance indicator should be shielded from the engine ignition system. The pressure balance indicator should also be shielded in order to eliminate the effect of the extraneous electrical interference.

2. The three resistances R_1 , R_2 , and R_3 should be replaced with resistances rated for one watt power. These resistances become very warm after a short period of use because of insufficient rating and probably contributed to the unsatisfactory operation of the indicator.

3. Because of difficulty experienced in maintaining proper electrode adjustment during the test, the electrode design should be modified so that it would be self-compensating for changes in engine operating temperature.

CHAPTER VIII
ACKNOWLEDGEMENTS

To the members of his Thesis Committee, Professors C. E. Trent, H. P. Marshall, and R. E. Will, the author wishes to express his sincere appreciation for their suggestions, cooperation, and support offered throughout the investigation.

The author wishes to express his personal gratitude to Professor J. B. Jones for his help and support offered during the course of this investigation.

To Professor H. L. Wood, the author wishes to express his indebtedness for invaluable aid received during the course of this investigation.

A special note of thanks is made to Professor J. P. Mahaney and to Mr. Mark B. Smith and the Staff of the Industrial Engineering Department's Machine Shop, without whose assistance the construction of the engine indicator would not have been possible.

The author wishes to thank Messrs. R. F. Stebar, R. D. Tate, Jr., H. M. Smith, F. H. Grissom, and A. N. Slusser, for their assistance in the setting up and operation of the apparatus.

BIBLIOGRAPHYA. Literature Cited

- (1) Dickenson, H. C., and Newell, F. B., A High Speed Engine Pressure Indicator of the Balanced Diaphragm Type. N. A. C. A. Report No. 107, 1920, pp 637, 638.
- (2) Insley, Robert, Engine Performance Characteristics. Kents Mechanical Engineers Handbook, Power section 13, p. 45.
- (3) Dickenson, H. C., and Newell, F. B., Op. Cit., p. 637.
- (4) Obert, E. F., Internal Combustion Engines, second edition. Scranton: International Textbook Company, 1950, p. 131.
- (5) Ibid, p. 132-134.
- (6) Dickenson, H. C., and Newell, F. B., Op. Cit., p. 638.
- (7) Ibid, p. 638.
- (8) Laserson, G. I., Construction and Calibration of a Laboratory Engine Pressure Indicator. Instruments, Vol. 24, 1951, p. 156.
- (9) Ibid, p. 157.
- (10) Taylor, E. S., and Draper, C. S., A New High Speed Engine Indicator. Mechanical Engineering, Vol. 55, 1933, p. 169.
- (11) Spanogle, J. A., and Collins, J. H., A Balanced Pressure Type of Maximum Cylinder Pressure Indicator. N. A. C. A. Technical Note, No. 359.
- (12) Roach, W. J. R., and Hempson, G. G., A Modified Farnboro Electric Indicator. The Engineer, Vol. 194, No. 5032, July 4, 1952, p. 7.

- (13) Church, D. R., and Hart, D. K., Balanced-Pressure Engine Indicator Development, Mechanical Engineering, Vol. 72, No. 5, pp. 389-391.
- (14) McCullough, J. D., Engine Cylinder Pressure Measurements. Paper presented to the Society of Automotive Engineers, January, 1953.
- (15) Taylor, E. S., and Draper, C. S., Op. Cit., p. 171.

B. Literature Examined

- (1) Morrison, J. C., Development of a High Speed Multipoint Indicator, The Engineer, Vol. 191, No. 4959, February, 1951, pp. 178-180.
- (2) Walshaw, T. D., The Effect of Phase Errors in Lime Base Indicator Diagrams, Engineering, Vol. 168, No. 4356, 1949, pp. 73-75.
- (3) Livingood, J. C., Improvement of the Accuracy of Balanced-Pressure Indicators and the Development of an Indicator Calibrating Machine, N. A. C. A. Tech Note, 1896, 1949.
- (4) Cornish and Mansfield, Obtaining Pressure Diagrams of Internal Combustion Engines, Engineering, Vol. 172, No. 4483, 1951, pp. 806-809.

APPENDIX

A. TABLES AND DIAGRAMS

TABLE I

TEST I

Throttle Setting - Full Spark Advance - 15° BTDC Compression Ratio-6.96:1
 Brake Load - 19 lb Brake Torque - 15.95 lb-ft Engine Speed - 1300 rpm
 Brake Horsepower - 3.29 Brake Mean Effective Pressure - 60.4 psi
 Friction Horsepower - 0.66 @ 550 rpm Barometer Reading 27.90 in.Hg

Reference Pressure	Crank Angle	Reference Pressure	Crank Angle	Reference Pressure	Crank Angle	Reference Pressure	Crank Angle
0 psig	-	130 psig	24° BTDC	100 psig	110° ATDC	6 in.Hg	-
10 "	-	140 "	20° "	90 "	120° "	8 " "	-
20 "	-	150 "	17° "	80 "	135° "	10 " "	-
30 "	-	160 "	15° "	70 "	175° "	12 " "	-
40 "	-	170 "	- "	60 "	180° "	14 " "	-
50 "	-	180 "	- "	50 "	200° "	16 " "	-
60 "	60° BTDC	170 "	- "	40 "	245° "	14 " "	-
70 "	55° "	160 "	- "	30 "	- "	12 " "	-
80 "	45° "	150 "	- "	20 "	- "	10 " "	-
90 "	40° "	140 "	- "	10 "	- "	8 " "	-
100 "	36° "	130 "	- "	0 "	- "	6 " "	-
110 "	32° "	120 "	96° ATDC	2 in.Hg	- "	4 " "	-
120 "	27° "	110 "	100° "	4 " "	- "	2 " "	-

TABLE II

TEST II

Throttle Setting - Full Spark Advance - 15° BTDC Compression Ratio - **6.96:1**
 Brake Load - 18 lb Brake Torque - 12.6 lb-ft Engine Speed - **1345 rpm**
 Brake Horsepower 3.23 Brake Mean Effective Pressure 57.2 psi
 Friction Horsepower 0.66 @ 550 rpm Barometer Reading 27.88 in.Hg

Reference Pressure	Crank Angle	Reference Pressure	Crank Angle	Reference Pressure	Crank Angle	Reference Pressure	Crank Angle
0 psig	-	130 psig	21° BTDC	100 psi	110° ATDC	6 in.Hg	-
10 "	-	140 "	18° "	90 "	120° "	8 " "	-
20 "	-	150 "	16° "	80 "	140° "	10 " "	-
30 "	100° BTDC	160 "	- "	70 "	175° "	12 " "	-
40 "	85° "	170 "	- "	60 "	180° "	14 " "	-
50 "	60° "	180 "	- "	50 "	200° "	16 " "	120° ATDC
60 "	57° "	170 "	- "	40 "	245° "	14 " "	-
70 "	49° "	160 "	- "	30 "	280° "	12 " "	-
80 "	42° "	150 "	- "	20 "	310° "	10 " "	-
90 "	37° "	140 "	- "	10 "	- "	8 " "	-
100 "	32° "	130 "	- "	0 "	- "	6 " "	-
110 "	29° "	120 "	96° ATDC	2 in.Hg	- "	4 " "	-
120 "	25° "	110 "	100° "	4 " "	- "	2 " "	-

TABLE III

TEST III

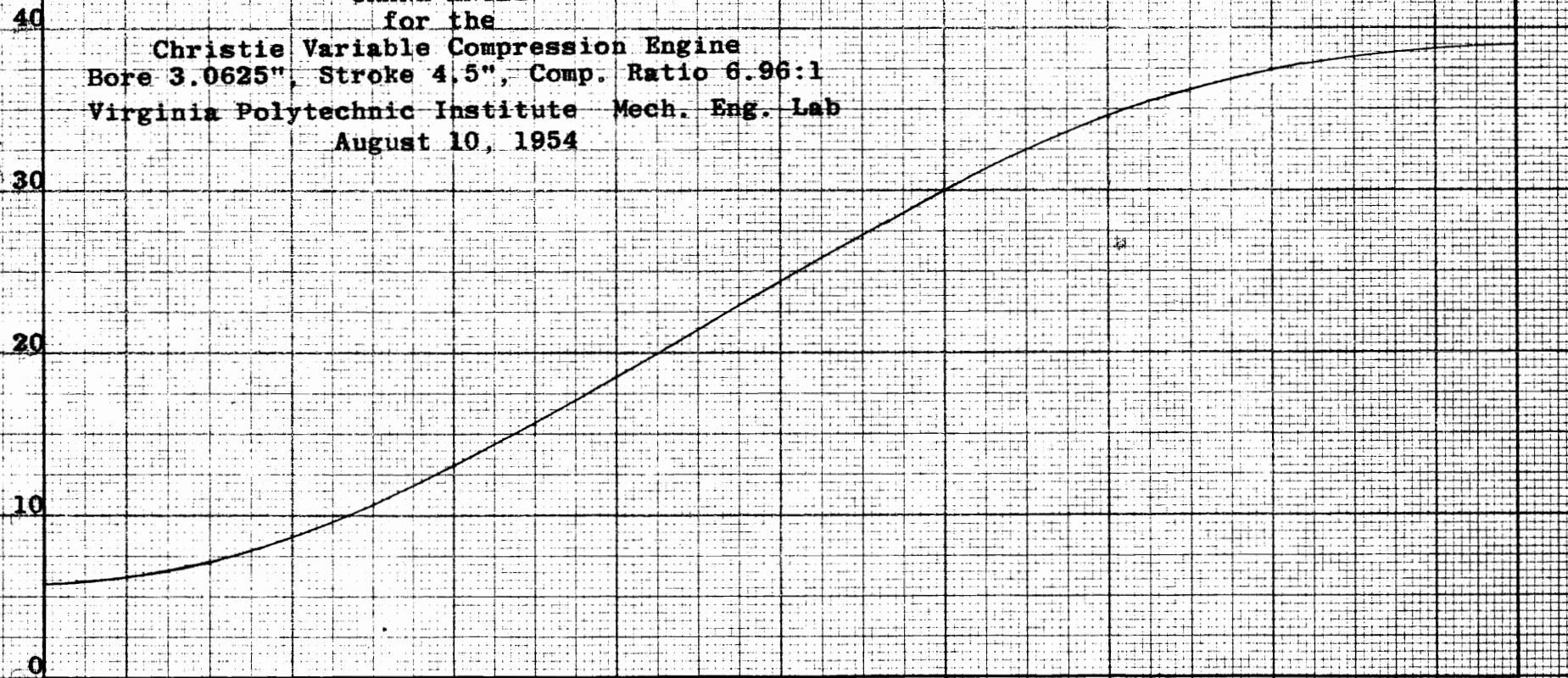
Throttle Setting - Full Spark Advance - 15° BTDC Compression Ratio - 6.96:1
 Brake Load - 15 lb Brake Torque - 12.6 lb-ft Engine Speed - 1370 rpm
 Brake Horsepower - 2.74 Brake Mean Effective Pressure 47.7 psi
 Friction Horsepower 0.66 @ 550 rpm Barometer Reading 27.88 in.Hg

Reference Pressure	Crank Angle	Reference Pressure	Crank Angle	Reference Pressure	Crank Angle	Reference Pressure	Crank Angle
0 psig	-	130 psig	20° BTDC	100 psig	97° ATDC	6 in. Hg	-
10 "	-	140 "	18° "	90 "	106° "	8 " "	-
20 "	114° BTDC	150 "	16° "	80 "	116° "	10 " "	19° ATDC
30 "	86° "	160 "	-	70 "	132° "	12 " "	22° "
40 "	70° "	170 "	-	60 "	151° "	14 " "	27° "
50 "	65° "	180 "	-	50 "	180° "	16 " "	- "
60 "	58° "	170 "	-	40 "	228° "	14 " "	- "
70 "	47° "	160 "	-	30 "	264° "	12 " "	- "
80 "	41° "	150 "	-	20 "	- "	10 " "	- "
90 "	35° "	140 "	-	10 "	- "	8 " "	- "
100 "	31° "	130 "	-	0 "	- "	6 " "	- "
110 "	29° "	120 "	83° ATDC	2 in. Hg	- "	4 " "	- "
120 "	22° "	110 "	90° "	4 " "	- "	2 " "	- "

CURVE I
CYLINDER VOLUME
VERSUS
CRANK ANGLE

for the
Christie Variable Compression Engine
Bore 3.0625", Stroke 4.5", Comp. Ratio 6.96:1
Virginia Polytechnic Institute Mech. Eng. Lab
August 10, 1954

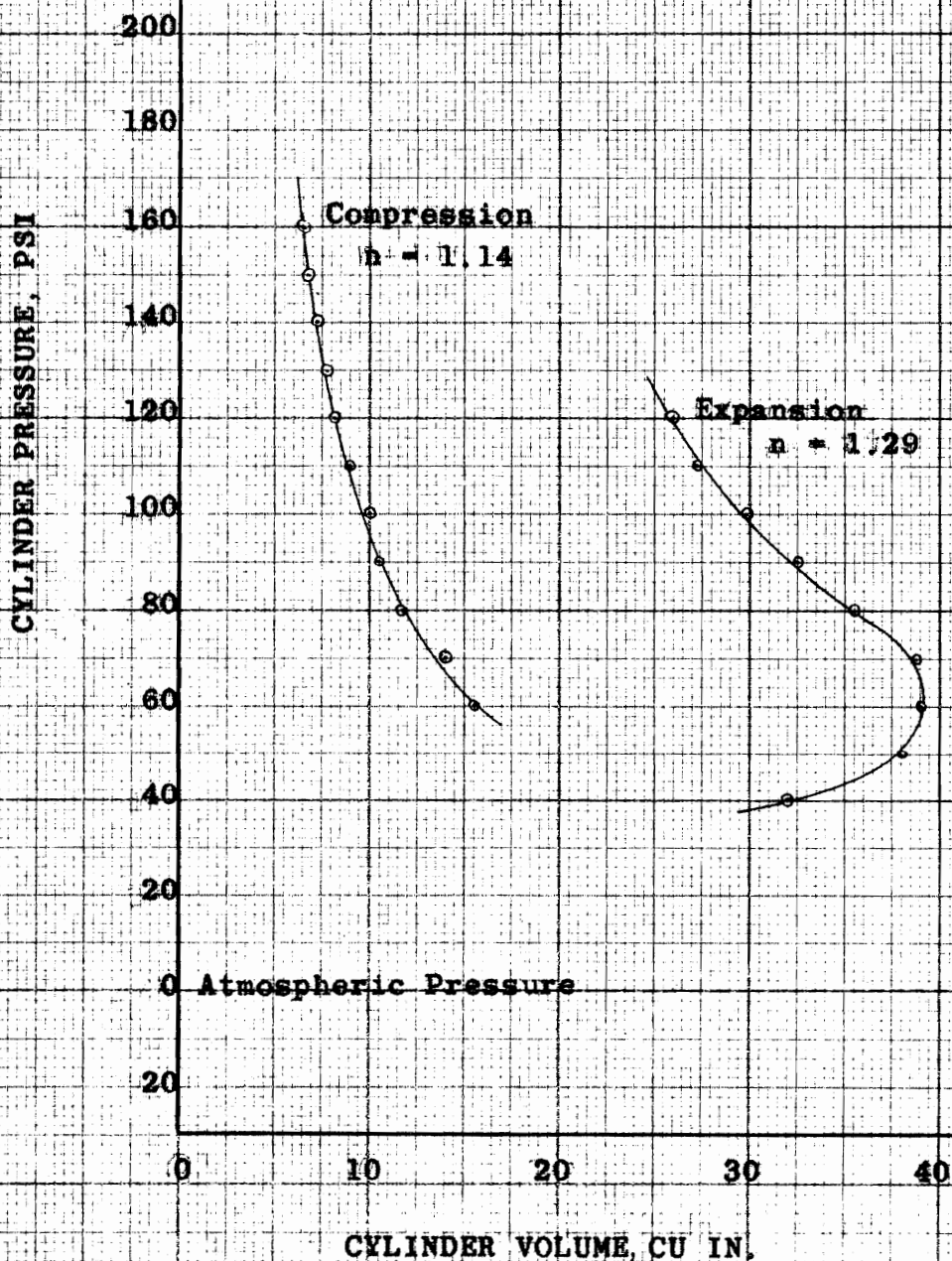
CYLINDER VOLUME, CU IN.



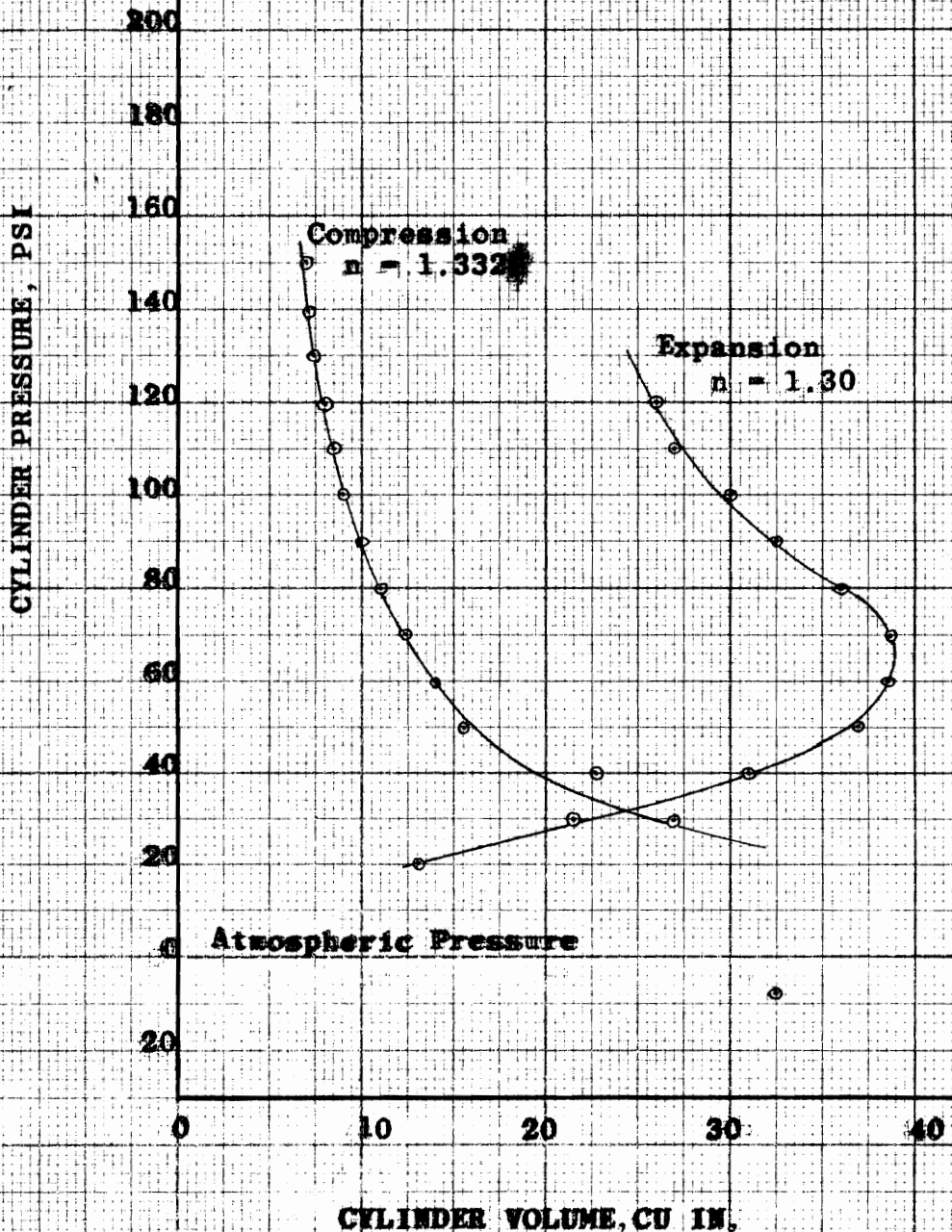
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
360 350 340 330 320 310 300 290 280 270 260 250 240 230 220 210 200 190

CRANK ANGLE, deg

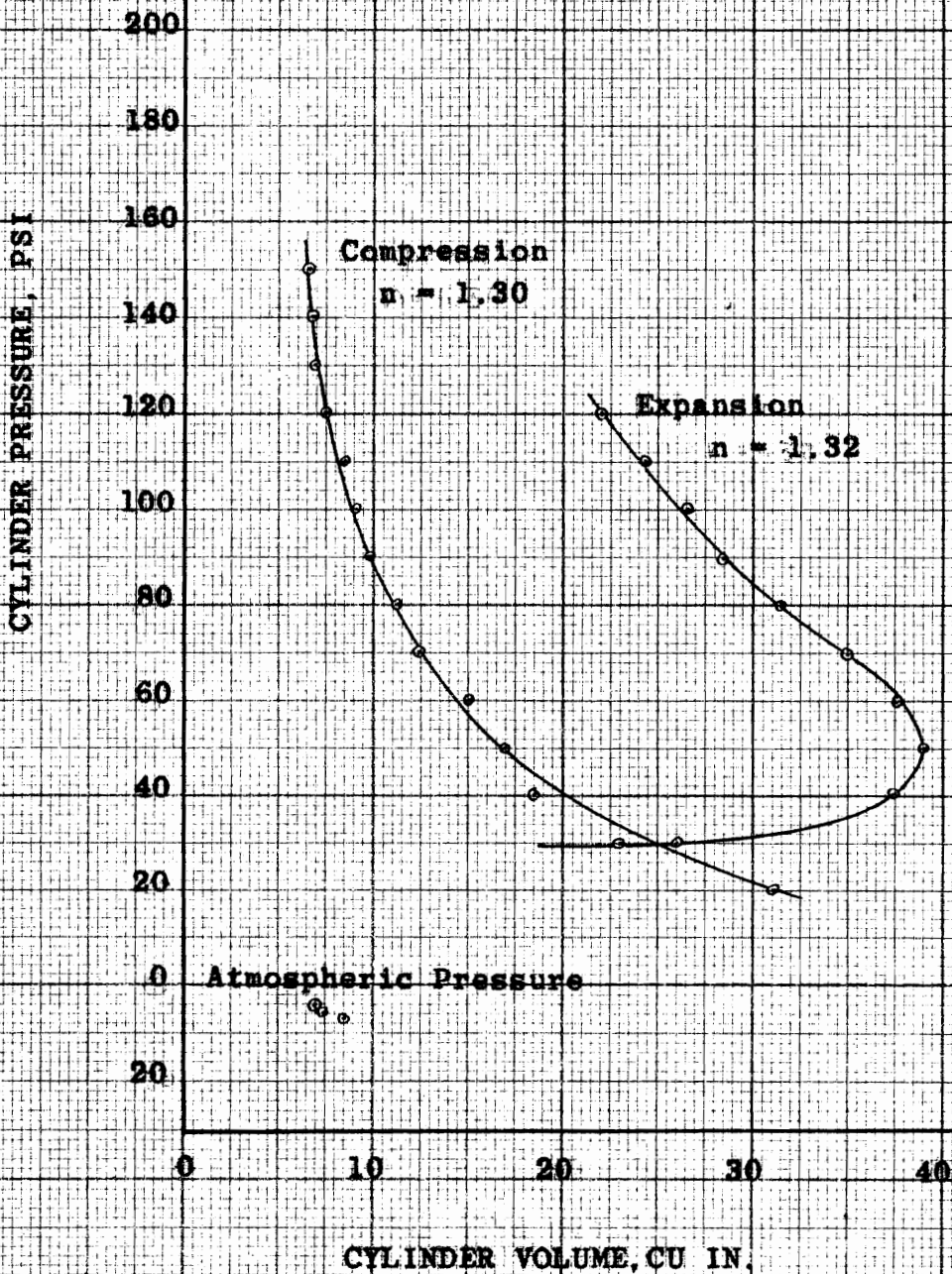
CURVE II
PRESSURE - VOLUME RELATIONS
For
TEST I
of the
BALANCED - PRESSURE DIAPHRAGM
ENGINE INDICATOR
Virginia Polytechnic Institute
August 11, 1954 Mech. Eng. Lab



CURVE III
PRESSURE - VOLUME RELATIONS
 for
TEST II
 of the
BALANCED - PRESSURE DIAPHRAGM
ENGINE INDICATOR
 Virginia Polytechnic Institute
 August 12, 1954 Mech. Eng. Lab.



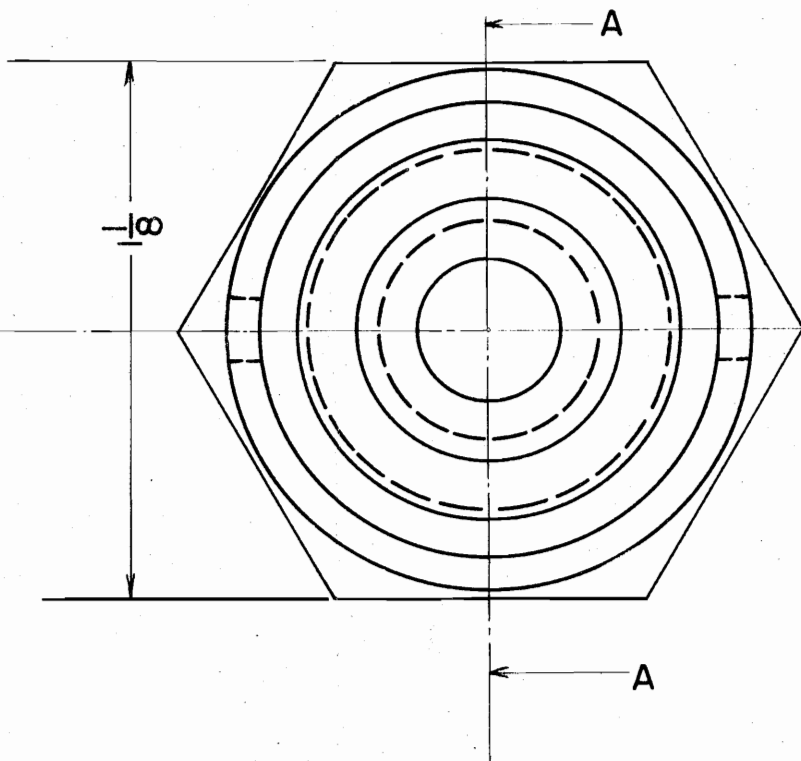
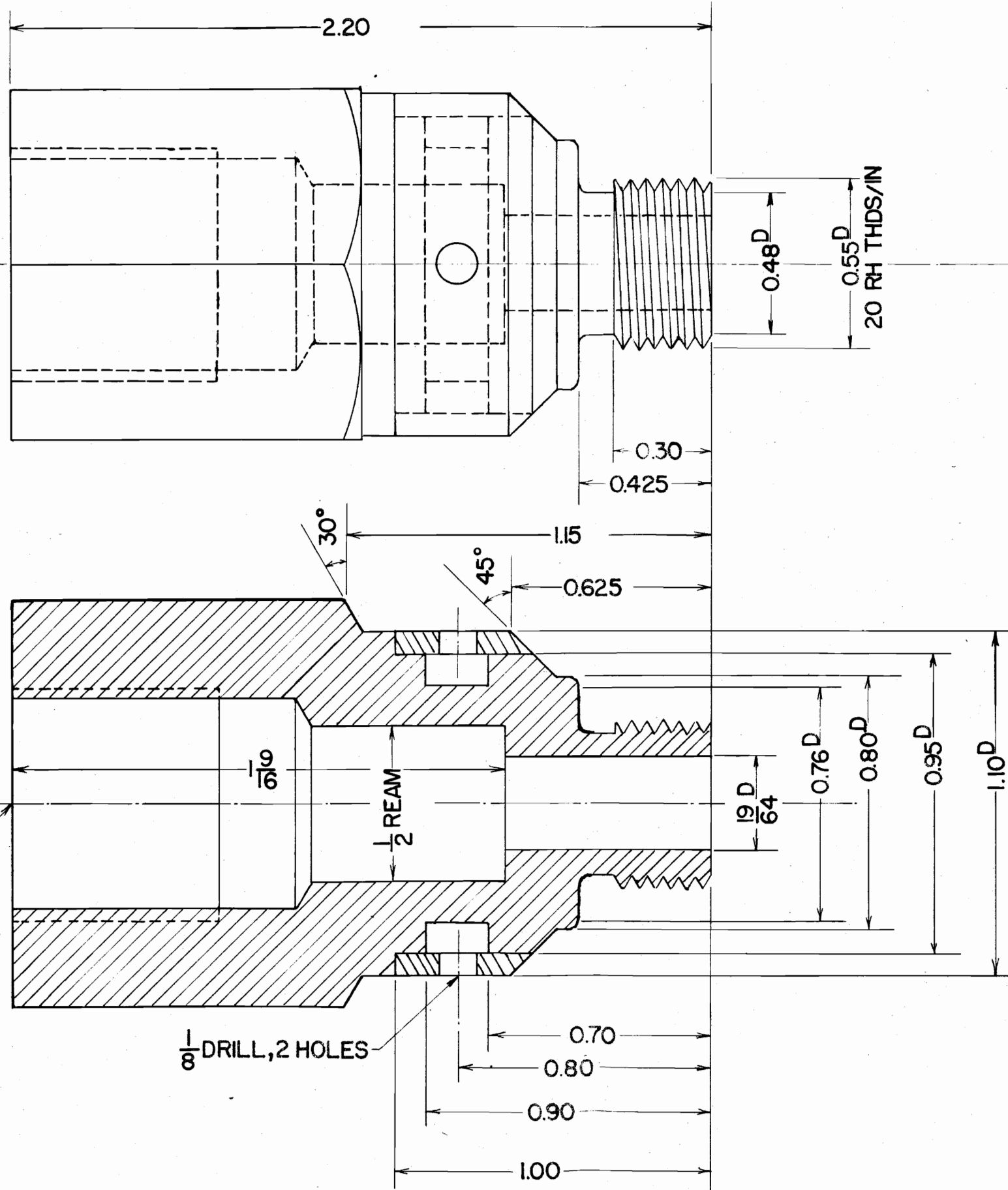
CURVE IV
PRESSURE - VOLUME RELATIONS
for
TEST III
of the
BALANCED - PRESSURE DIAPHRAGM
ENGINE INDICATOR
 Virginia Polytechnic Institute
 August 13, 1954 Mech. Eng. Lab



B. INDICATOR DRAWINGS

$\frac{11}{16}$ DRILL X $\frac{7}{8}$ DEEP, $\frac{3}{4}$ -16 NF-2, $\frac{21}{32}$ DEEP

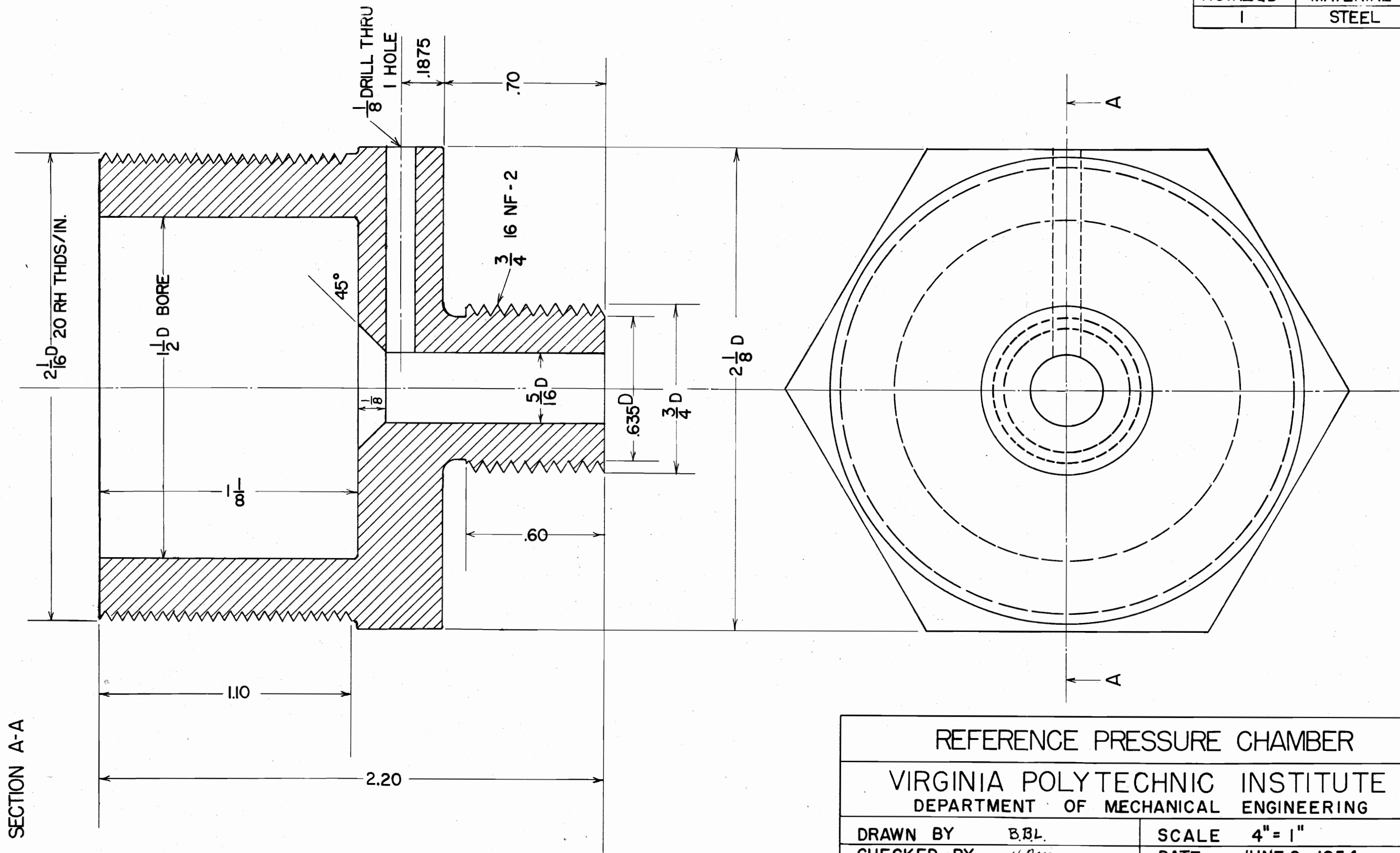
SECTION A-A



NO. REQ D	MATERIAL
I	STEEL

DIAPHRAGM HOLDER	
VIRGINIA POLYTECHNIC INSTITUTE DEPARTMENT OF MECHANICAL ENGINEERING	
DRAWN BY BBL	DATE JUNE 15, 1954
CHECKED BY <i>NPM</i>	SCALE 4" = 1"
APPROVED BY <i>CET</i>	DRAWING NO. I

NO. REQD	MATERIAL
1	STEEL



REFERENCE PRESSURE CHAMBER

VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF MECHANICAL ENGINEERING

DRAWN BY B.B.L.

SCALE 4" = 1"

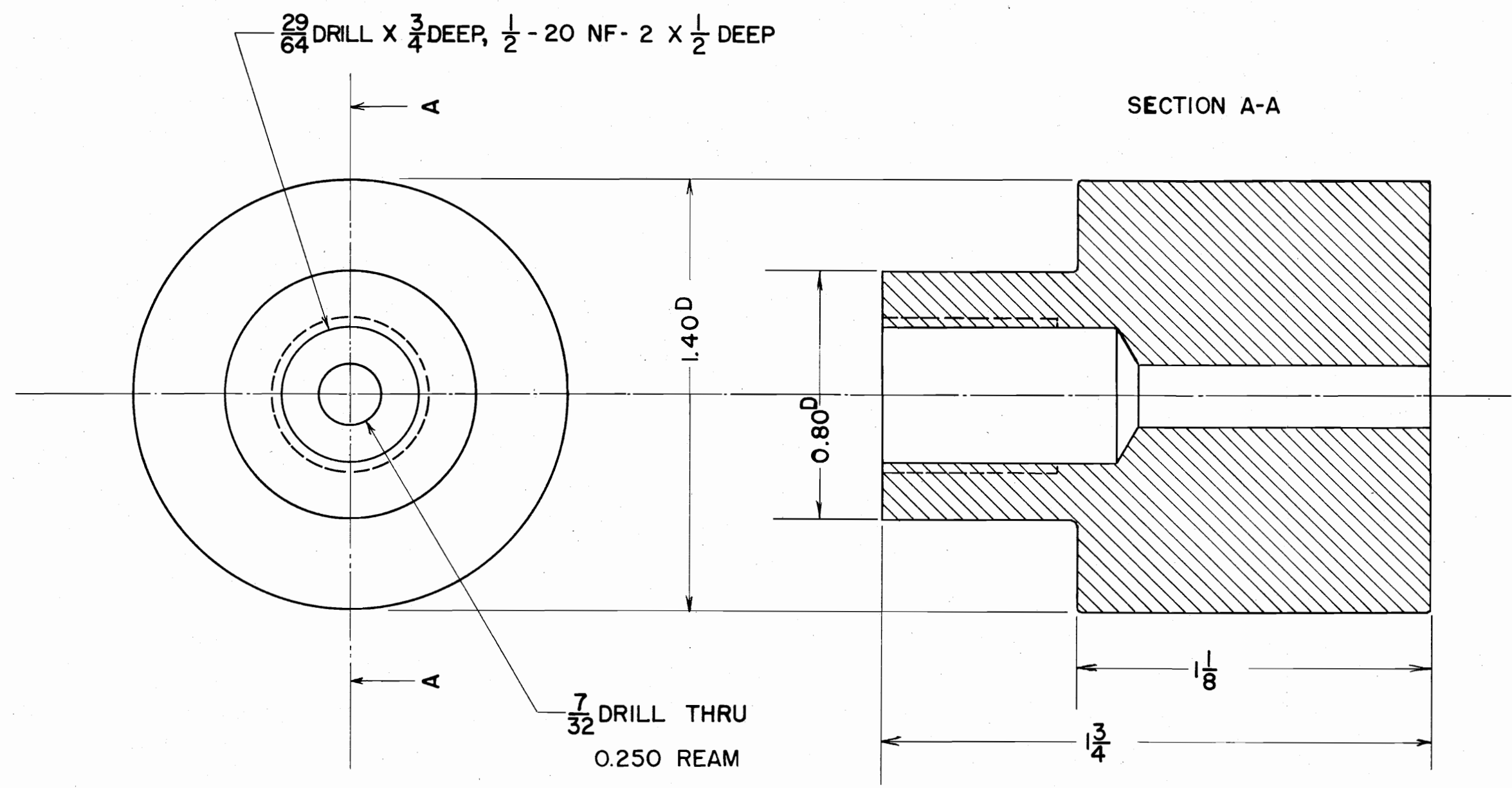
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DATE JUNE 2, 1954

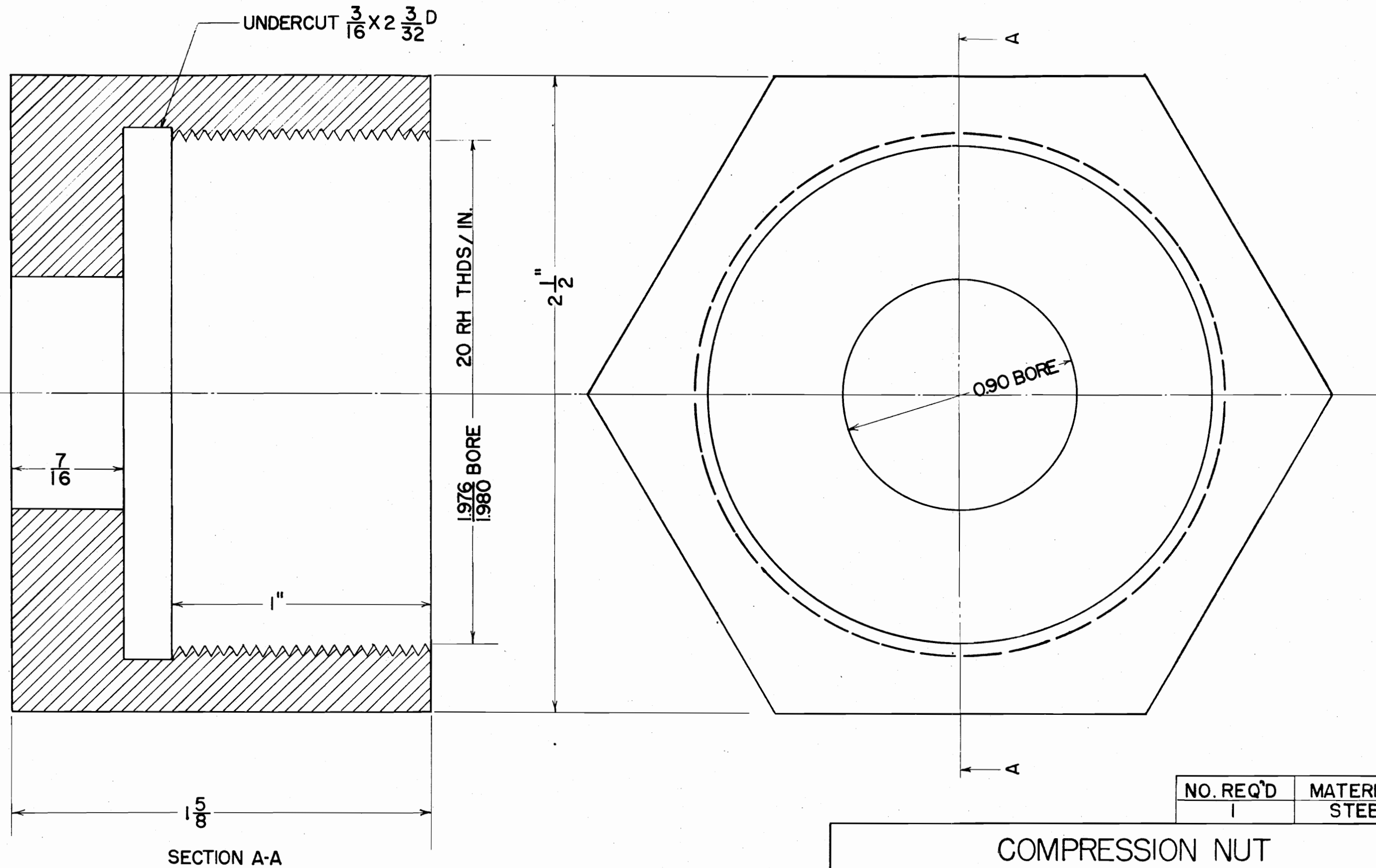
APPROVED BY *C.E.Z.*

DRAWING NO. 2

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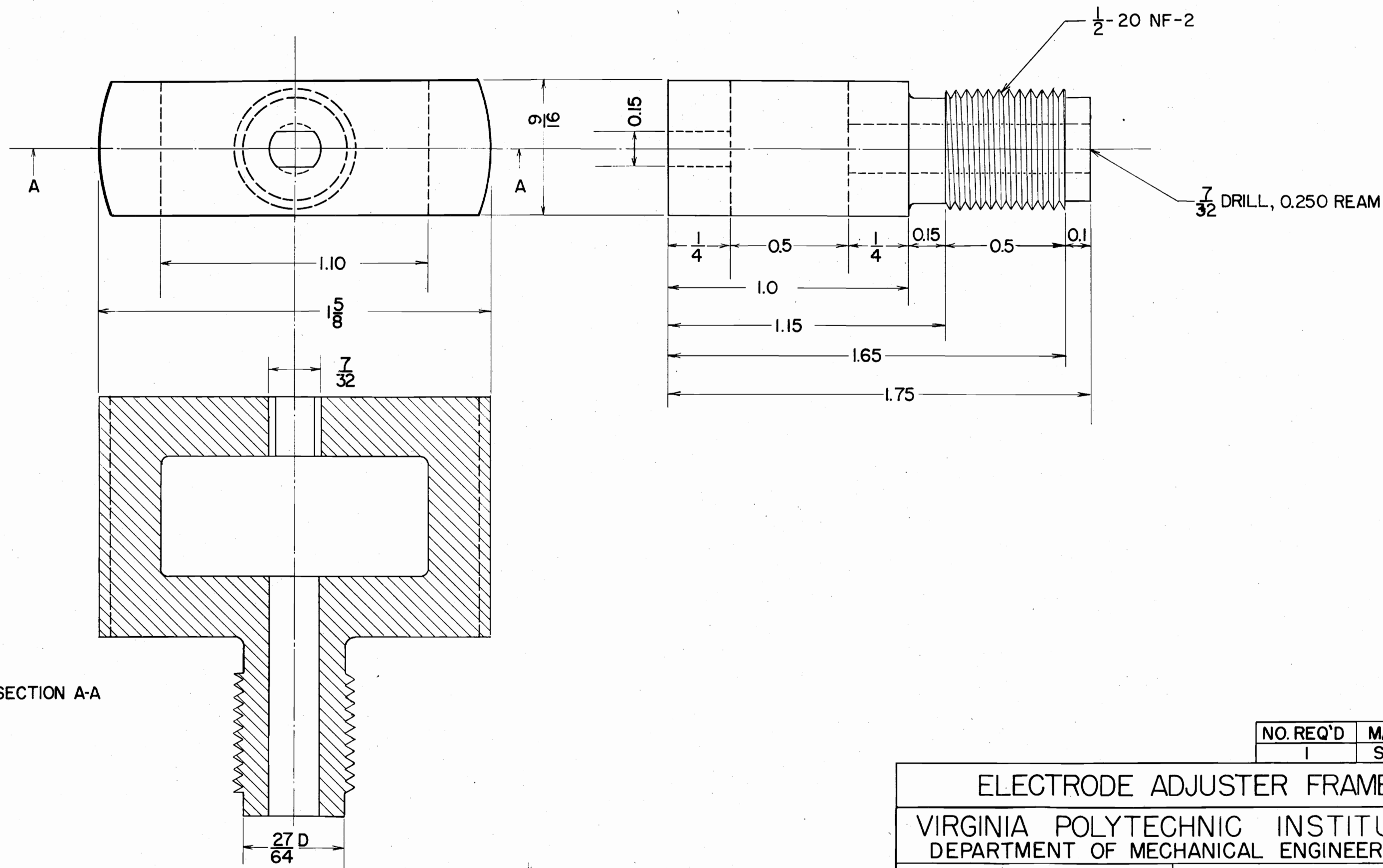


ELECTRODE GUIDE	
VIRGINIA POLYTECHNIC INSTITUTE DEPARTMENT OF MECHANICAL ENGINEERING	
DRAWN BY B.B.L.	SCALE 4" = 1"
CHECKED BY <i>APM</i>	DATE JUNE 7, 1954
APPROVED BY <i>C.E.T.</i>	DRAWING NO. 3



NO. REQ'D	MATERIAL
1	STEEL

COMPRESSION NUT	
VIRGINIA POLYTECHNIC INSTITUTE DEPARTMENT OF MECHANICAL ENGINEERING	
DRAWN BY <i>BBL</i>	SCALE 4"=1"
CHECKED BY <i>NRM</i>	DATE JUNE 4, 1954
APPROVED BY <i>C&J</i>	DRAWING NO. 4



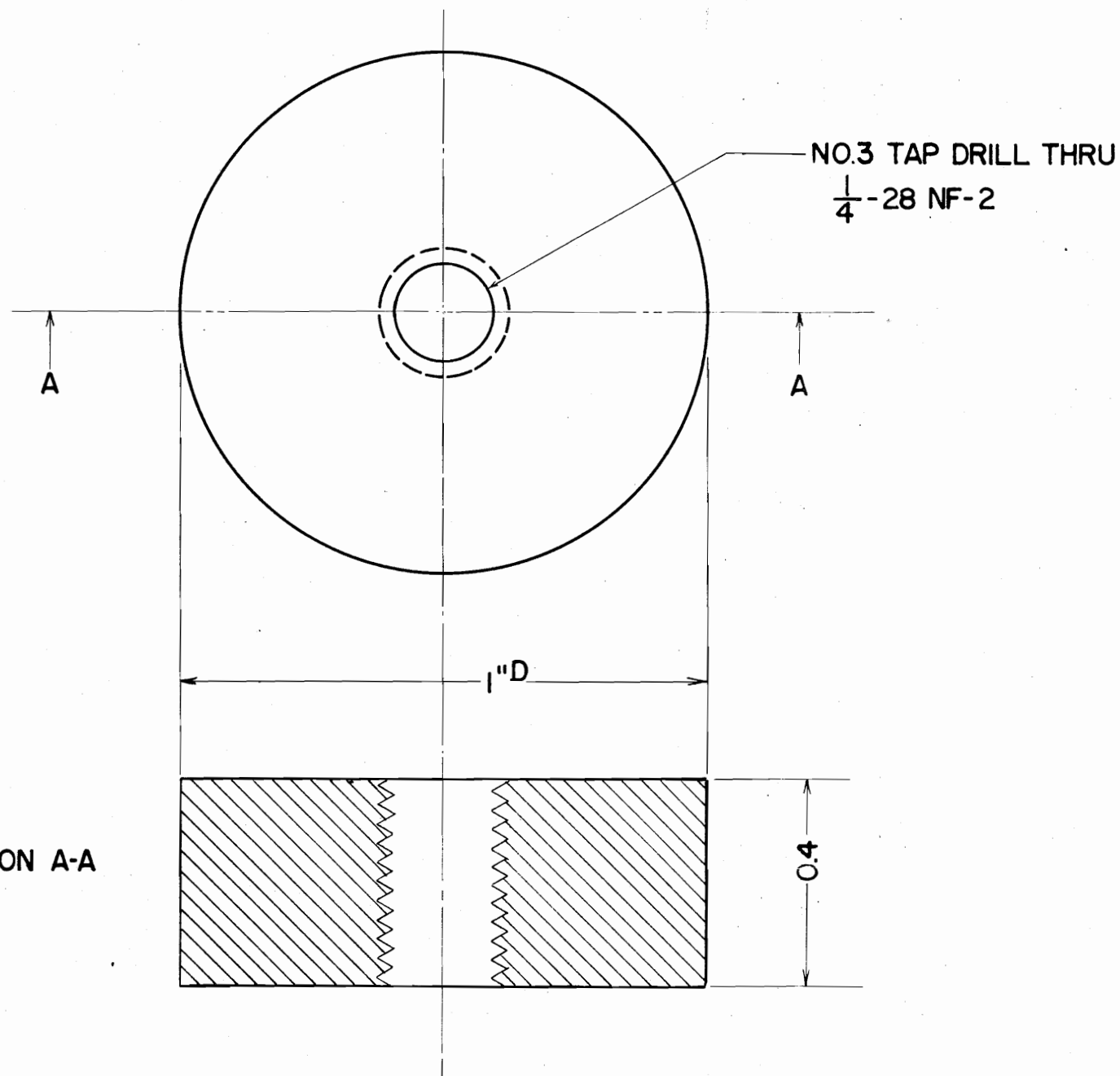
SECTION A-A

NO. REQ'D	MATERIAL
1	STEEL

ELECTRODE ADJUSTER FRAME

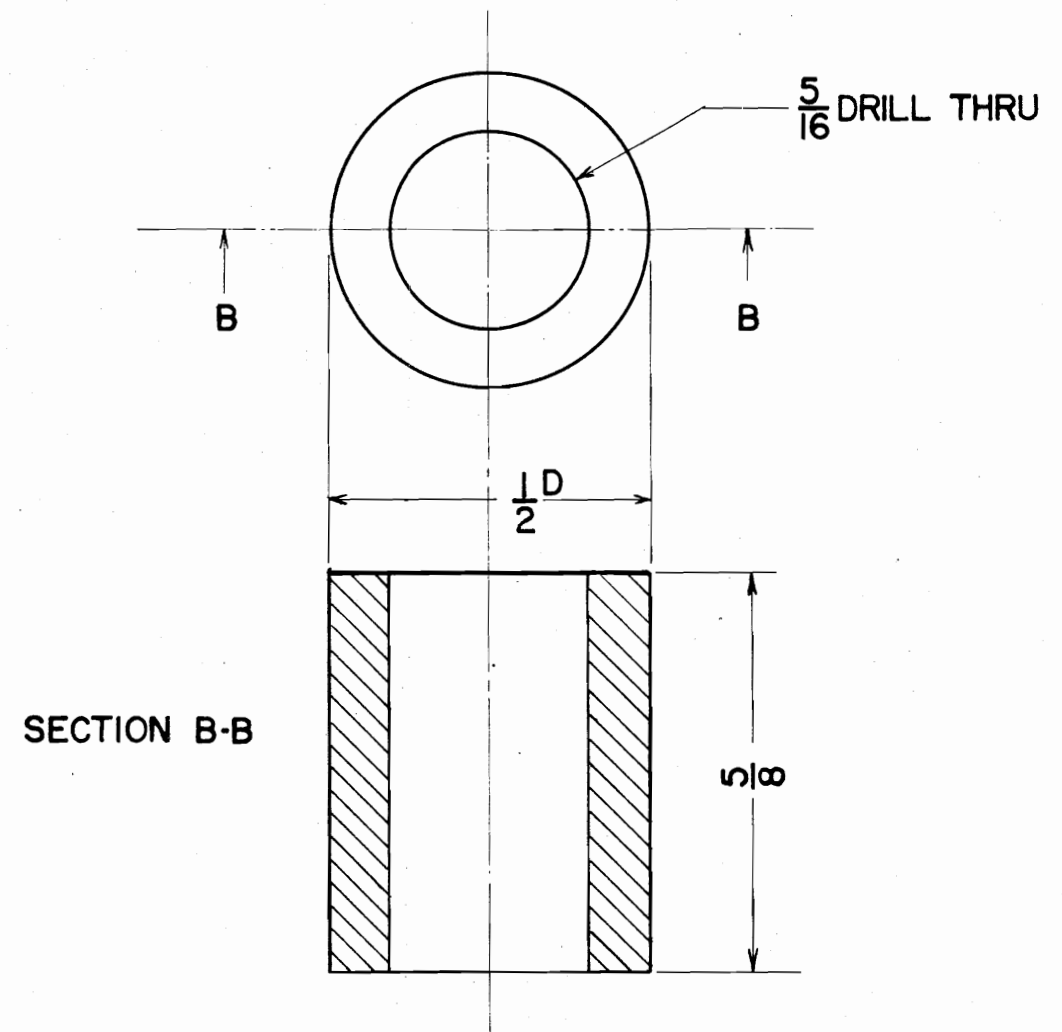
VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF MECHANICAL ENGINEERING

DRAWN BY <i>BBL</i>	DATE JUNE 9, 1954
CHECKED BY <i>NAM</i>	SCALE 4" = 1"
APPROVED BY <i>CEY</i>	DRAWING NO. 5



ELECTRODE ADJUSTER NUT

NO. REQ'D	MATERIAL
2	STEEL



DIAPHRAGM PRESSURE RING

NO. REQ'D	MATERIAL
1	STEEL

INDICATOR COMPONENTS

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DRAWN BY BBL.

DATE JUNE 11, 1954

CHECKED BY *JRM*

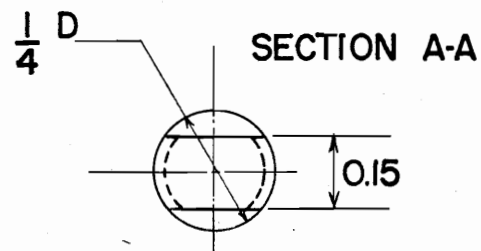
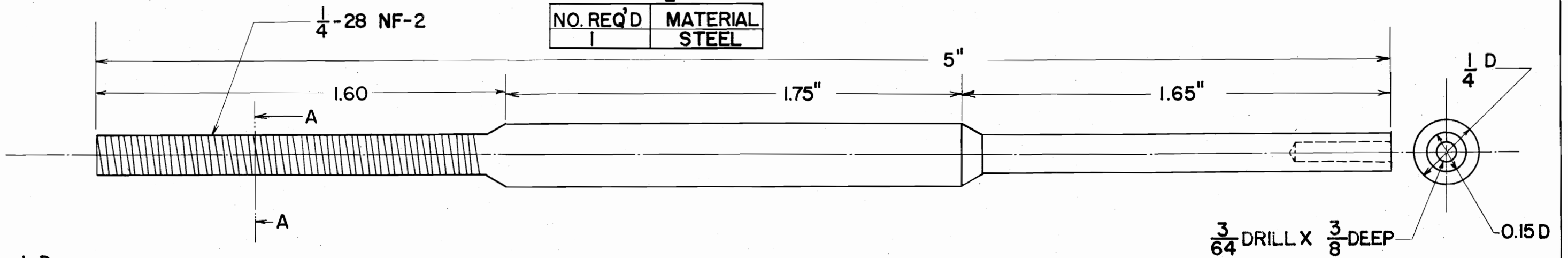
SCALE 3" = 1"

APPROVED BY *CET*

DRAWING NO. 6

FIG. 1
INDICATOR ELECTRODE
SCALE $2\frac{1}{2}''=1''$

NO. REQ'D	MATERIAL
1	STEEL



SPOTFACE 0.30D X 0.006 DEEP

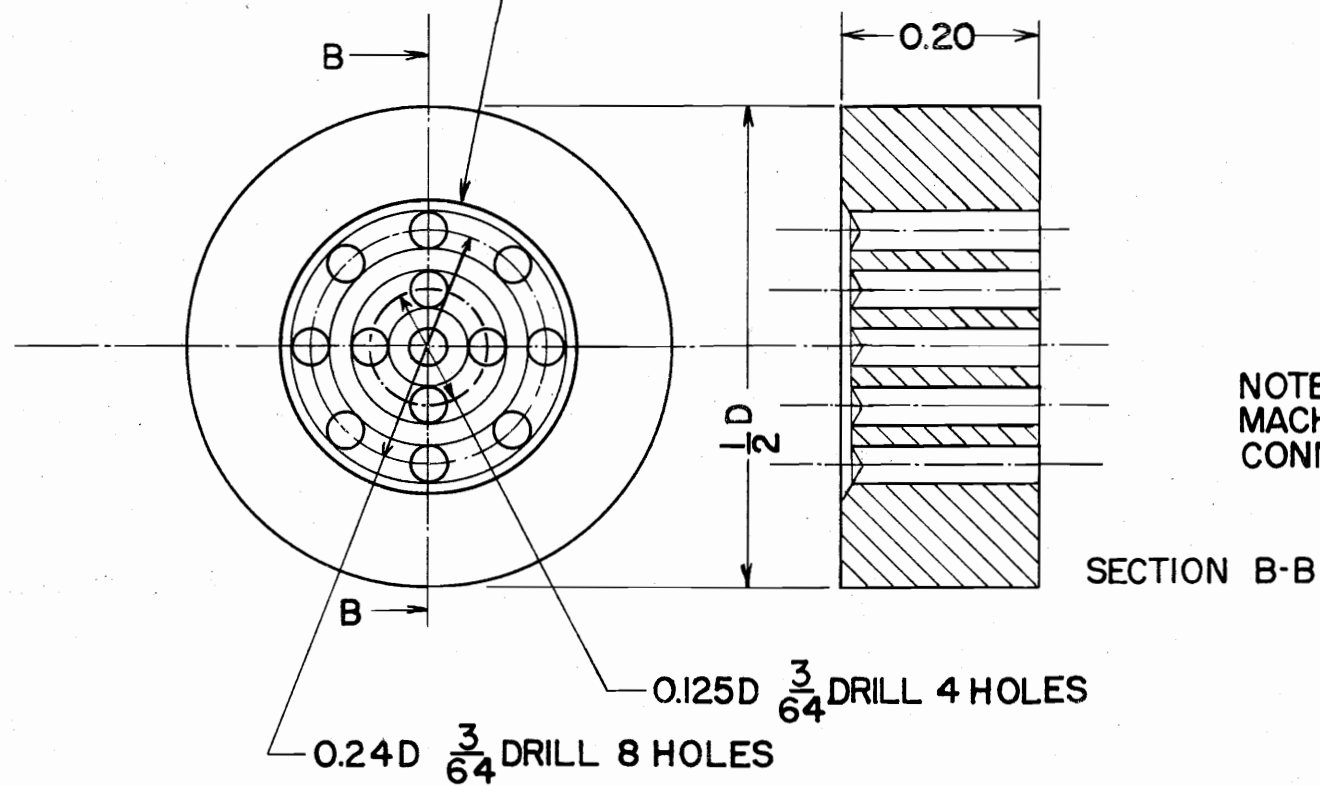


FIG. 2
DIAPHRAGM LOWER SUPPORT
SCALE $5''=1''$

NO. REQ'D	MATERIAL
1	STEEL

NOTE:
MACHINE CONCENTRIC V-GROVES
CONNECTING HOLES

INDICATOR COMPONENTS

VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF MECHANICAL ENGINEERING

DRAWN BY <i>BBL</i>	DATE JUNE 15, 1954
CHECKED BY <i>NPM</i>	SCALE AS SHOWN
APPROVED BY <i>C.E.T.</i>	DRAWING NO. 7

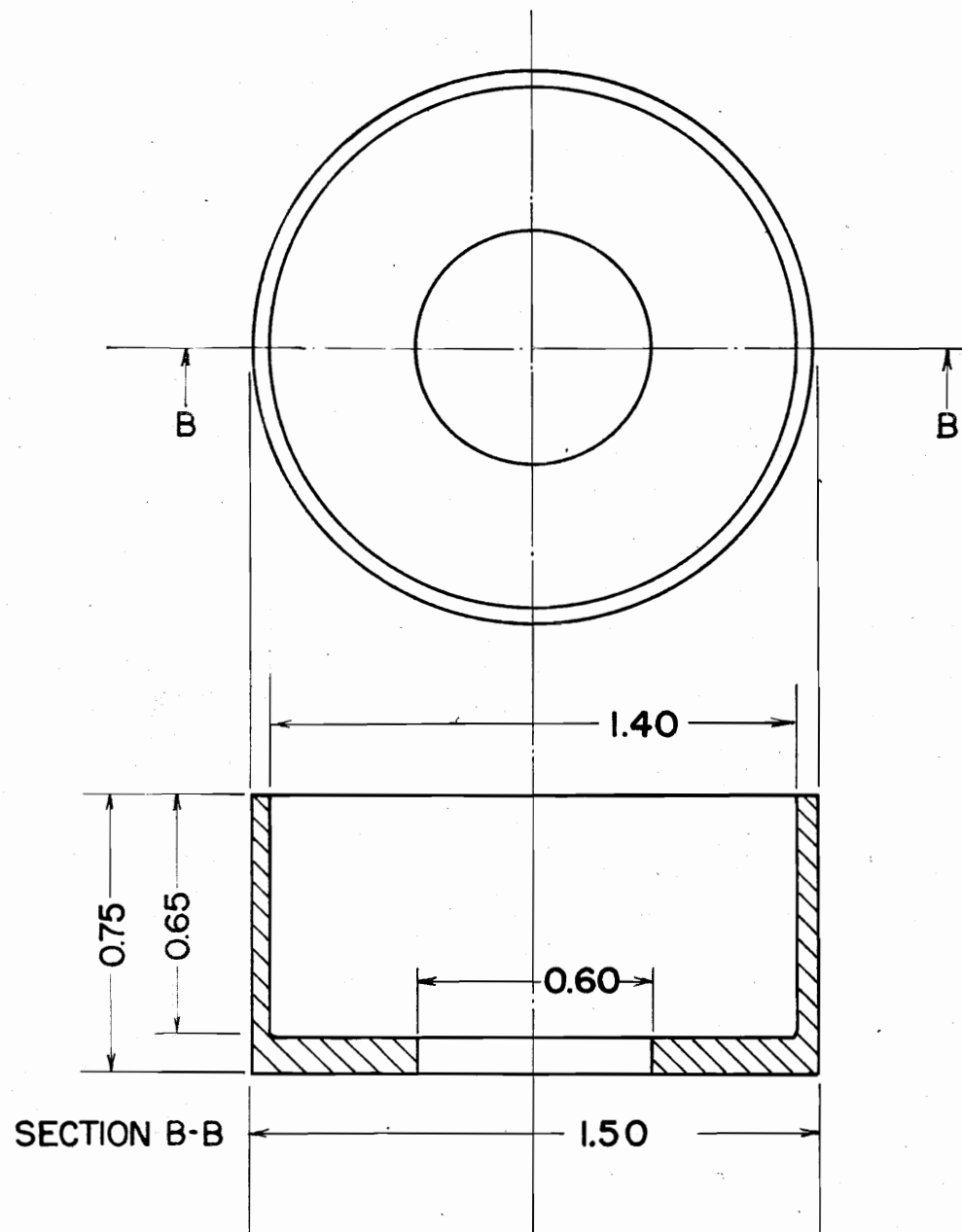
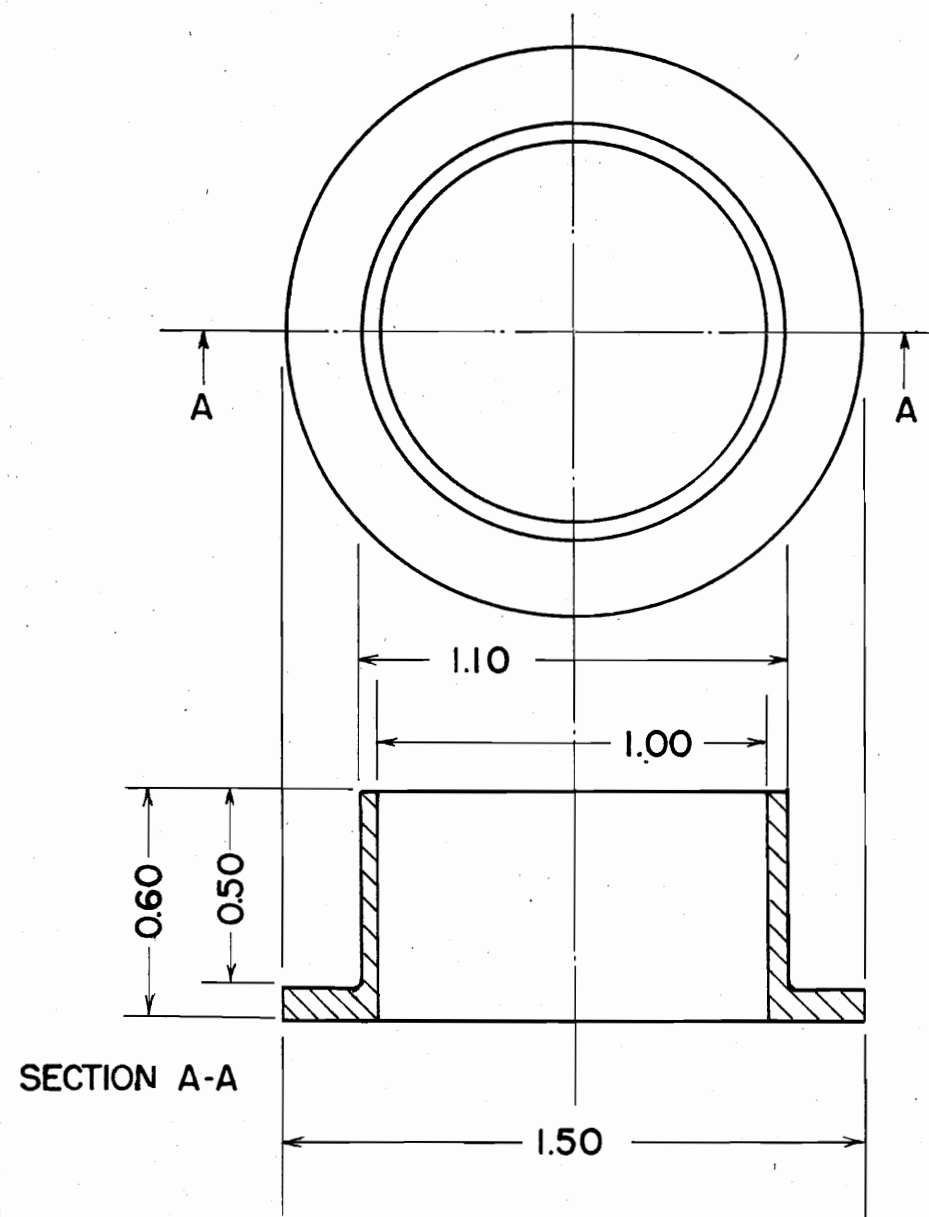


FIG. 1

TEFLON INSULATORS

SCALE 3" = 1"

NO. REQ D	MATERIAL
1 EACH	TEFLON

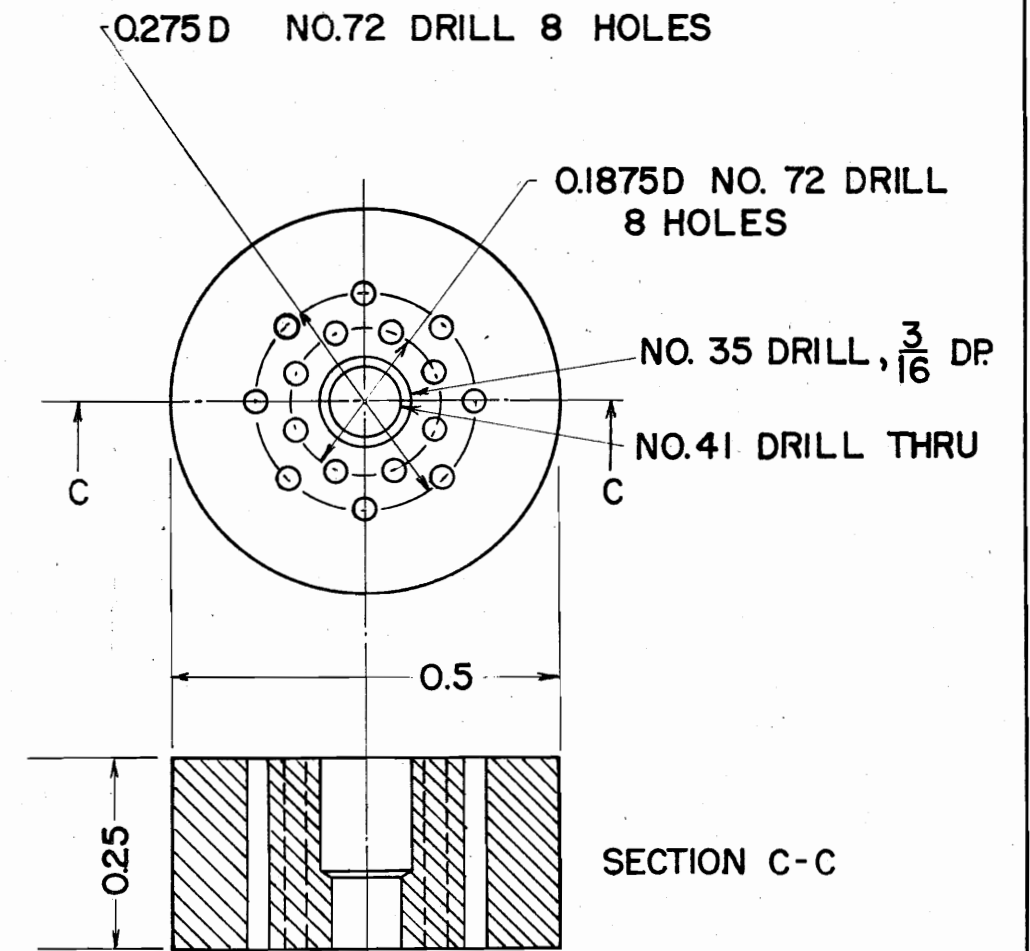


FIG. 2

DIAPHRAGM UPPER SUPPORT

NO. REQ D	MATERIAL
1	STEEL

SCALE 4" = 1"

INDICATOR COMPONENTS

VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF MECHANICAL ENGINEERING

DRAWN BY: *B.B.L.*

DATE: JULY 26, 1954

CHECKED BY: *NAM*

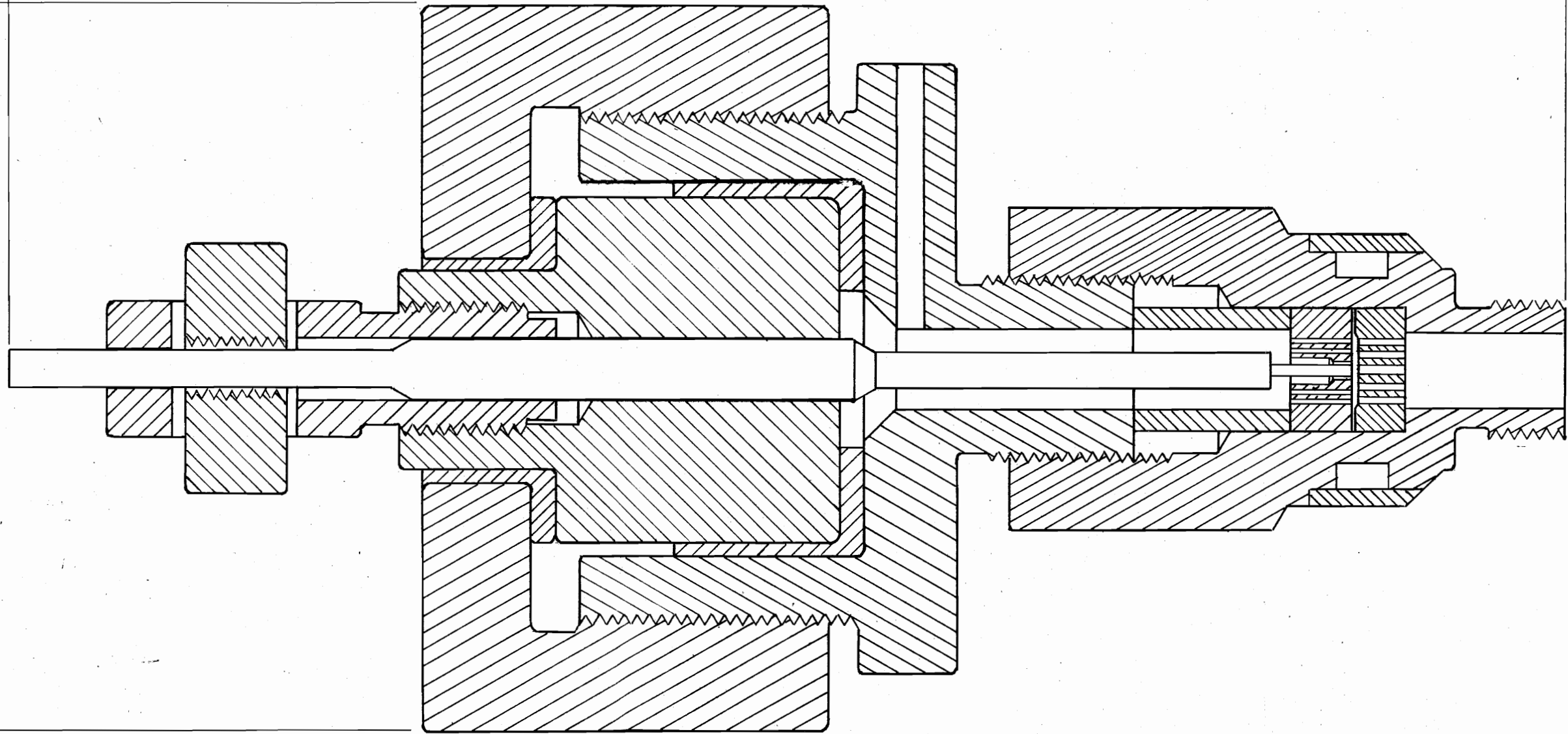
SCALE: AS SHOWN

APPROVED BY: *CEA*

DRAWING NO. 8

6.15

2.90



INDICATOR ASSEMBLY

VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF MECHANICAL ENGINEERING

DRAWN BY: B.B.L.

SCALE 2"=1"

CHECKED BY: *W.M.*

DATE JULY 26, 1954

APPROVED BY: C.E.T.

DRAWING NO. 9

VITA

The author was born in Rural Hall, suburb of Winston-Salem, North Carolina, on October 31, 1931. Following the death of his Mother he moved to Blacksburg, Virginia, in the spring of 1933, to live with his Aunt and Uncle, Mr. and Mrs. L. C. Beamer.

He attended the Blacksburg District Elementary School and was graduated from Blacksburg High School in 1949. He entered Virginia Polytechnic Institute that fall and was graduated in 1953, with a Bachelor of Science Degree, whereupon he entered the Graduate School in Mechanical Engineering as a graduate assistant.



Benton B. Lindamood